Neutrino Physics, SNO, and SNOLAB

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- Status of Neutrino Physics, ongoing motivation for solar neutrinos, double beta decay
- Status of SNO, SNOLAB
- Future experiments at SNOLAB

Neutrino Physics

What have we learned?

Neutrino properties

1) Evidence for neutrino flavor change:

- Atmospheric: Super-K
- Solar: SNO (Solar model independent test, supported by other measurements).
- LSND?: MiniBoone does not see effects compatible with oscillation at LSND
- Neutrino parameter limits set by many experiments: Reactor, Accelerator

2) Neutrino Mass:

- Mass differences from oscillations
- Mass Limit < 2.8 eV from tritium beta decay
- Double Beta Decay: Limits so far: Mass limit < ~ 0.35 eV if Majorana.
- Limits from Astrophysics: Large Scale structure < 1 eV.

3) Number of light neutrinos:

- Z width: 2.981 +- 0.008 active types
- Big Bang Nucleosynthesis: ~ 3 active neutrino types
- No specific evidence for sterile neutrinos.
- Limits on sterile from solar, atmospheric measurements.

Neutrino properties

-The most favored explanation for the data to date is Neutrino Oscillations of 3 active neutrino types.

-Other possibilities are not completely ruled out, but less favored
- Flavor Changing Neutral Currents
- Resonant Spin Flavor Precession for solar neutrinos
- Violation of Equivalence Principle
- CPT Violation
- Sterile neutrinos

In the discussion to follow, I will concentrate on the favored basis of Neutrino Oscillations of three active neutrino types and consider the further information to be obtained on this basis.

Using the oscillation framework:

If neutrinos have mass: $|\nu_l\rangle = \sum U_{li} |\nu_i\rangle$

For 3 Active neutrinos. (MiniBoone has recently ruled out LSND result)

$$U_{li} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

Maki-Nakagawa-Sakata-Pontecorvo matrix

(Double β decay only)

$$= \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{-i\delta} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & 1 & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{-i\alpha_2/2} & 0 \\ 0 & 0 & e^{-i\alpha_3/2+i\delta} \end{pmatrix}$$

✔ Solar,Reactor | ✔ Atmospheric | ? CP Violating Phase | ? Reactor, Accel. | ? Majorana Phases

$where\ c_{ij} = \cos\theta_{ij},\ and\ s_{ij} = \sin\theta_{ij}$

Range defined for Δm_{12}, Δm_{23} ✔

For two neutrino oscillation in a vacuum: (valid approximation in many cases)

$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta \sin^2(1.27 \frac{\Delta m^2 L}{E})$$

Matter Effects – the MSW effect

(Mikheyev, Smirnov, Wolfenstein)

$$i\frac{d}{dt}\begin{bmatrix}\nu_e\\ \nu_x\end{bmatrix} = H\begin{bmatrix}\nu_e\\ \nu_x\end{bmatrix}$$

$$H = \begin{bmatrix} -\frac{\Delta m^2}{4E}\cos 2\theta + \boxed{\sqrt{2}G_F N_e} & \frac{\Delta m^2}{4E}\sin 2\theta \\ \frac{\Delta m^2}{4E}\sin 2\theta & \frac{\Delta m^2}{4E}\cos 2\theta \end{bmatrix}$$

The extra term arises because solar ν_e have an extra interaction via W exchange with electrons in the Sun or Earth.

In the oscillation formula:

$$\sin^2 2\theta_m = \frac{\sin^2 2\theta}{(\omega - \cos 2\theta)^2 + \sin^2 2\theta}$$

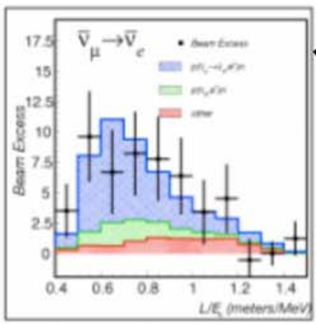
$$\omega = -\sqrt{2}G_F N_e E / \Delta m^2$$

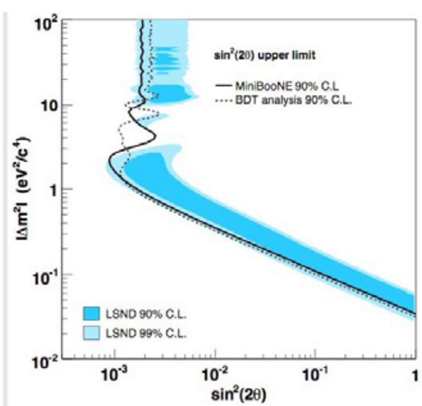
MSW effect can produce an energy spectrum distortion and flavor regeneration in Earth giving a Day-night effect

Neutrino LANDscape

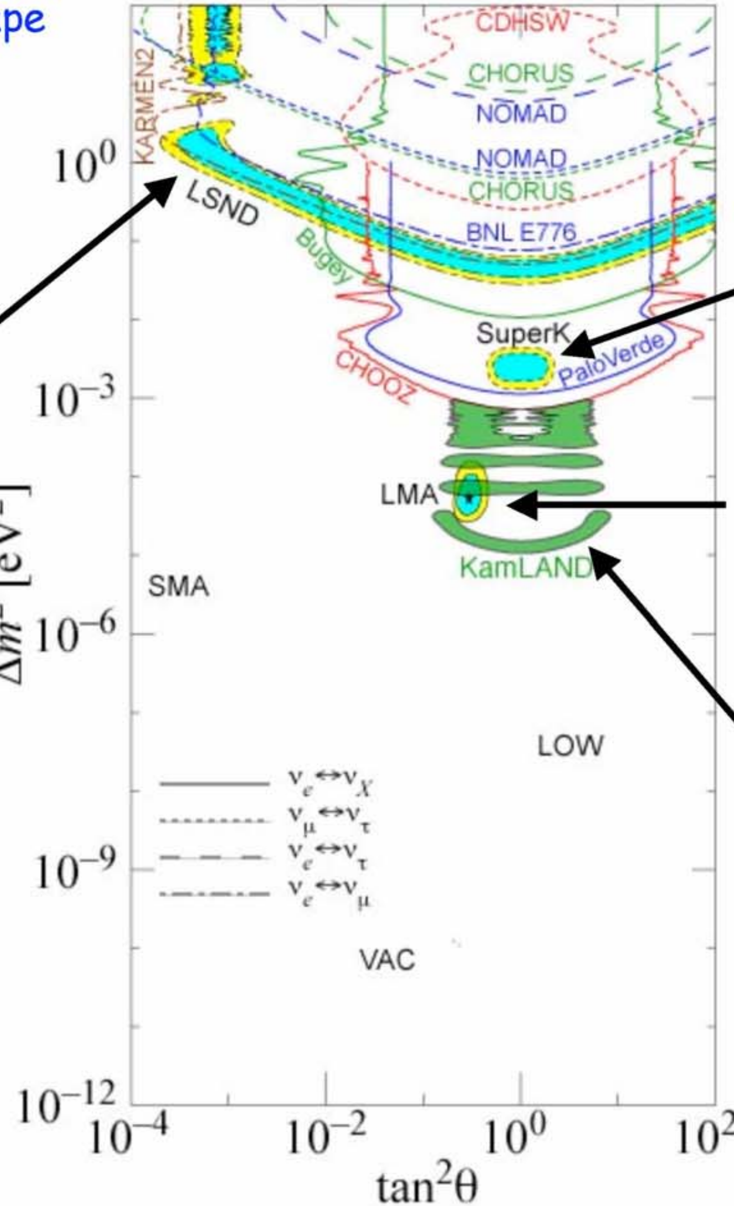
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

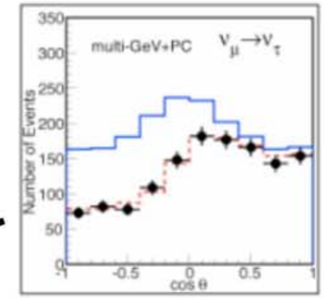
LSND





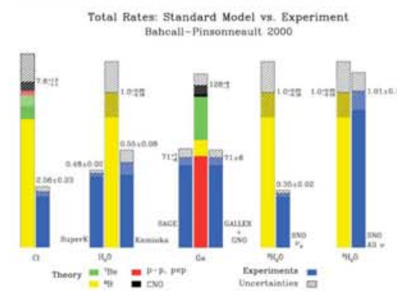
Now ruled out
By MiniBoone





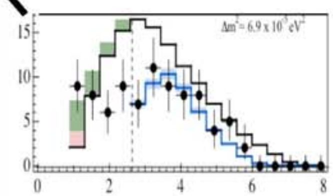
SuperK

$\nu_\mu \rightarrow \nu_\tau$



Solar

$\nu_e \rightarrow \nu_x$

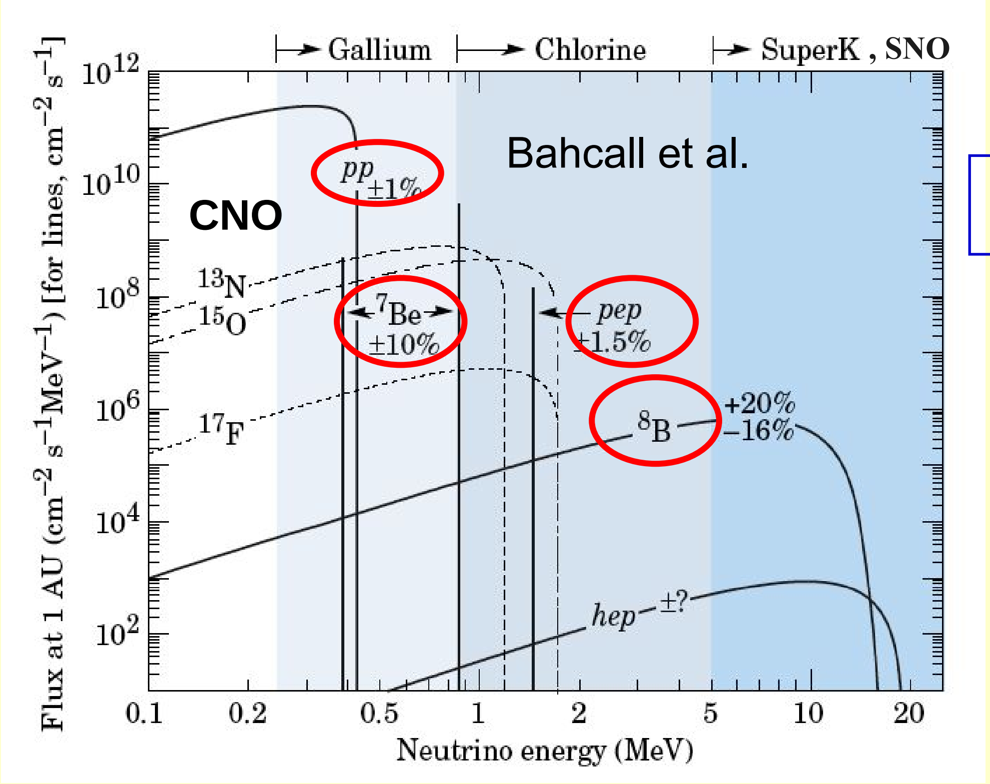


Reactor

$\bar{\nu}_e \rightarrow \bar{\nu}_x$

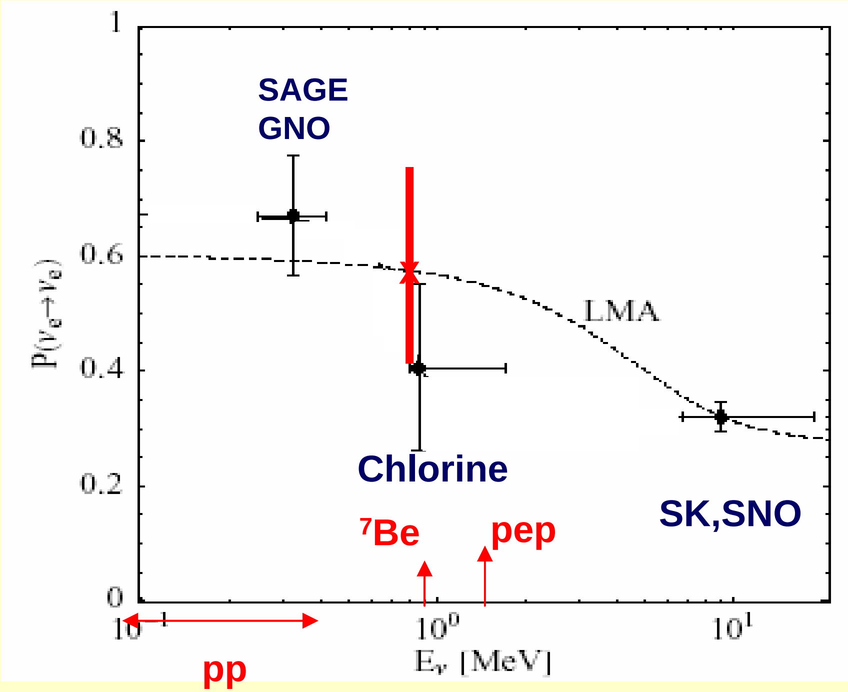
Oscillations for Solar Neutrinos

Solar Model Flux Calculations



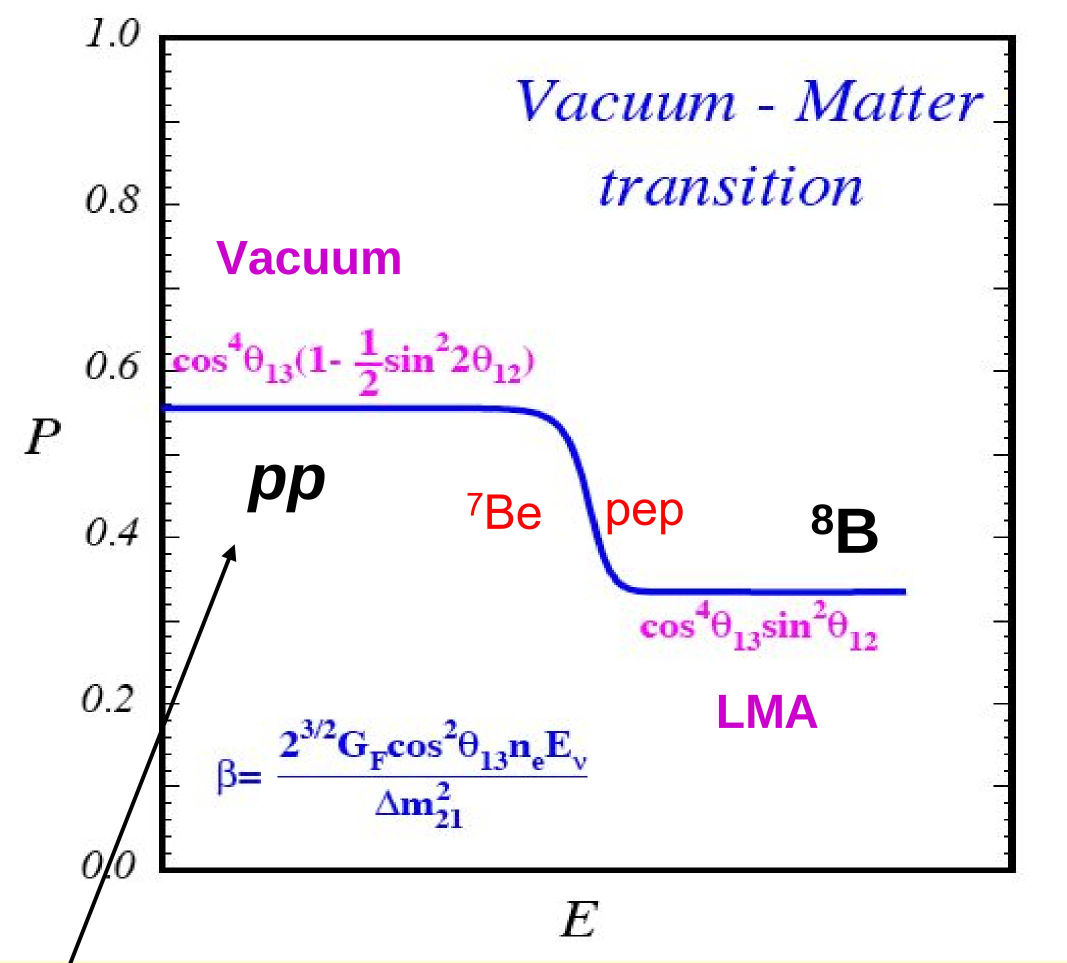
Matter Interaction Effect:LMA

Current Data for ν_e Survival



New ^{7}Be result from Borexino agrees with LMA Mixing parameters With ~ 30% accuracy

Future solar neutrino measurements
pp, ^{7}Be, pep, ^{8}B



- **Compare ES, CC**
- **Compare ES, SSM**

Bahcall & Pena-Garay
hep-ph/0305159

- **NEUTRINO PHYSICS**

- Confirm matter effects (MSW).

- Improve Θ_{12}, Θ_{13}.

- Search for effects of sterile ν, Non-Standard Interactions, Mass-varying neutrinos.

- **SOLAR PHYSICS**

- Accurate measurement of neutrino luminosity (pp, pep).

- Observe CNO neutrinos.

The Sudbury Neutrino Observatory: SNO

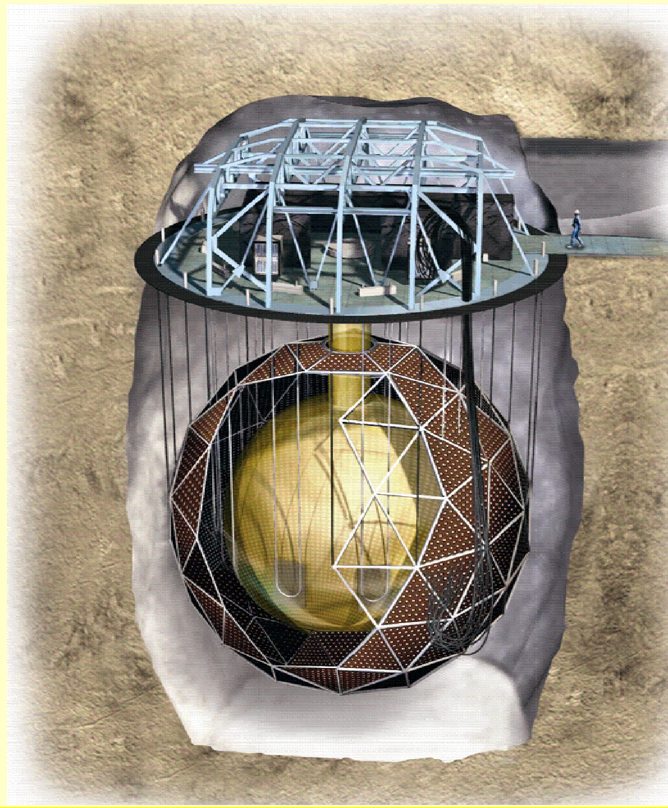
Acrylic vessel (AV)
12 m diameter

1000 tonnes D_2O
($300 million)

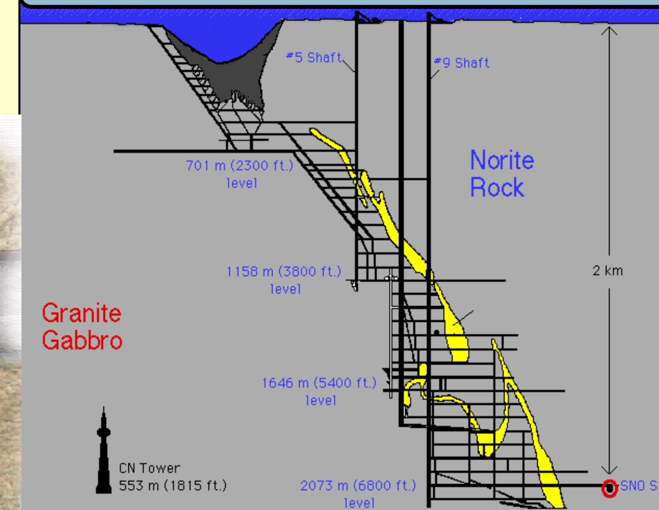
1700 tonnes H_2O
inner shielding

5300 tonnes H_2O
outer shielding

~9500 PMT's



6800 feet (~2km) underground

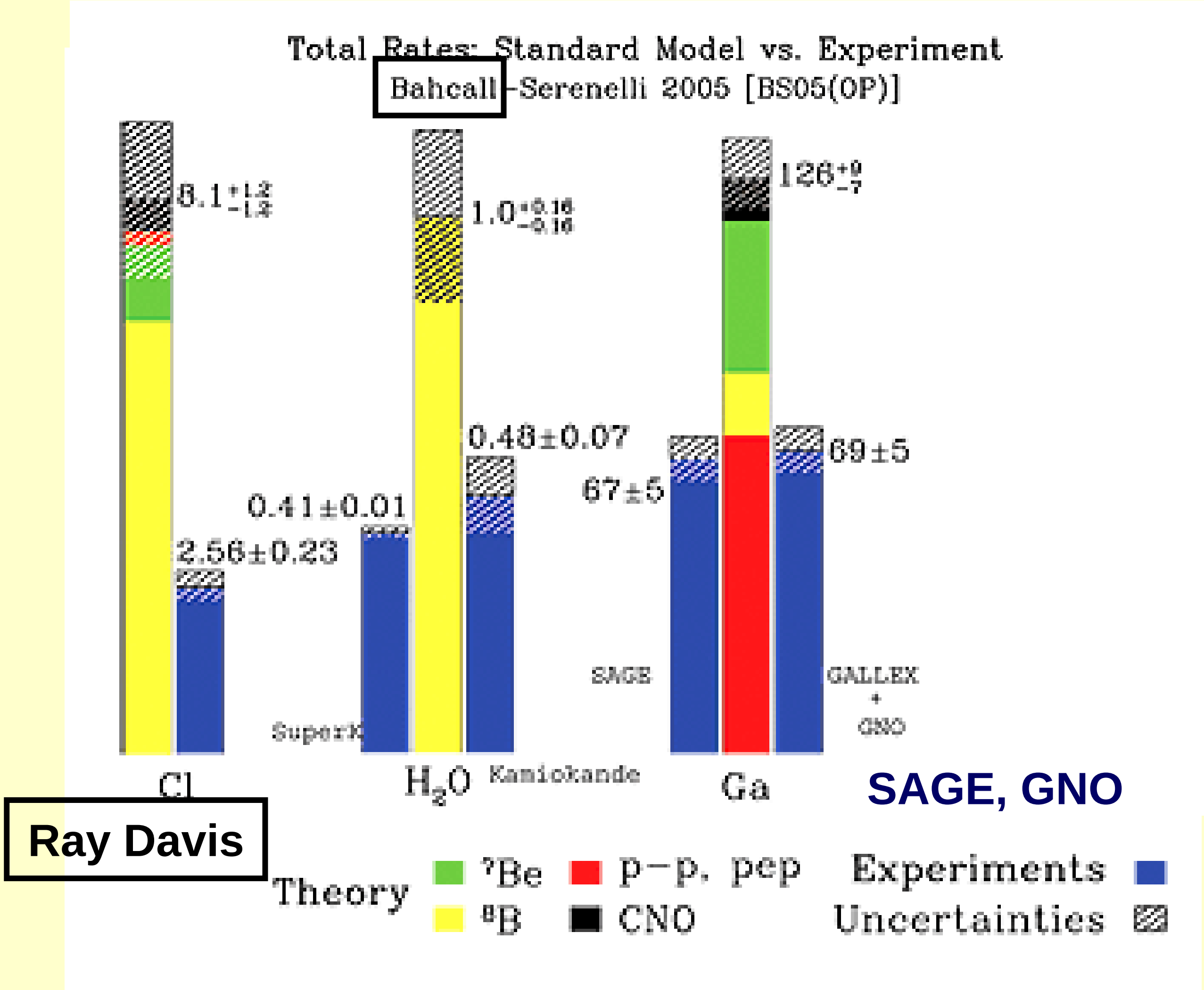


Creighton mine
Sudbury, CA

"The Sudbury Neutrino Observatory" , The SNO Collaboration
Nuclear Instruments and Methods in Physics Research A449 (2000) pp. 172-207

The heavy water has recently been returned and development work is in progress on SNO+ with liquid scintillator and ^{150}Nd additive

Experiments sensitive primarily or exclusively to Electron Neutrinos saw too few neutrinos compared to Solar Models



"Solar Neutrino Problem"

1967 - 2001

Question: Were the solar model calculations inaccurate, Or were the neutrinos changing to other undetected types?

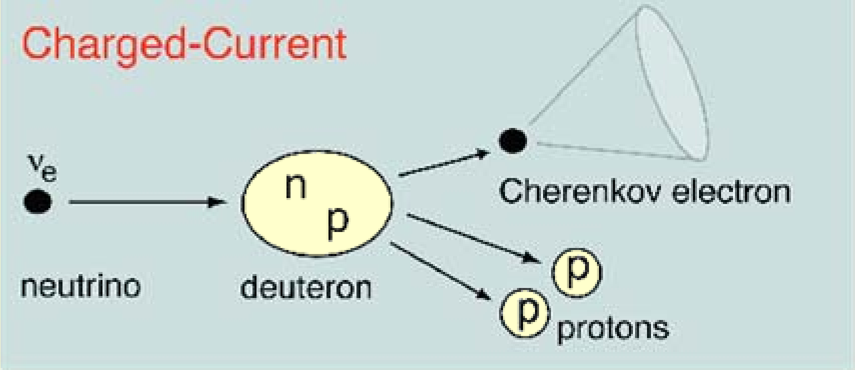
Unique Signatures in SNO (D_2O)

Charged-Current (CC)

$\nu_e + d \rightarrow e^- + p + p$

$E_{thresh} = 1.4$ MeV

ν_e only

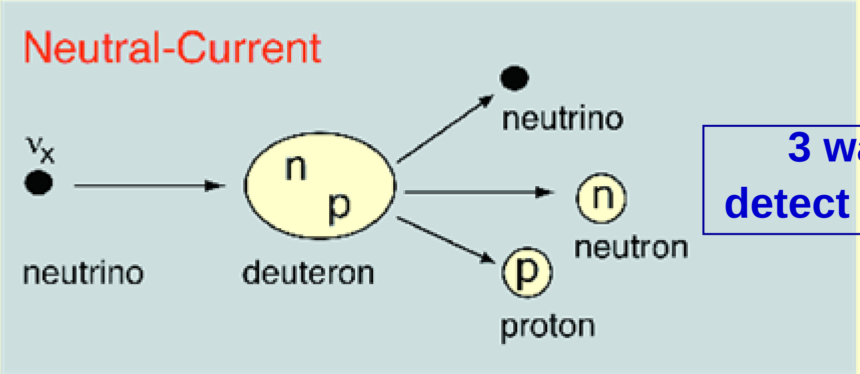


Neutral-Current (NC)

$\nu_x + d \rightarrow \nu_x + n + p$

$E_{thresh} = 2.2$ MeV

Equally sensitive to $\nu_e\, \nu_\mu\, \nu_\tau$

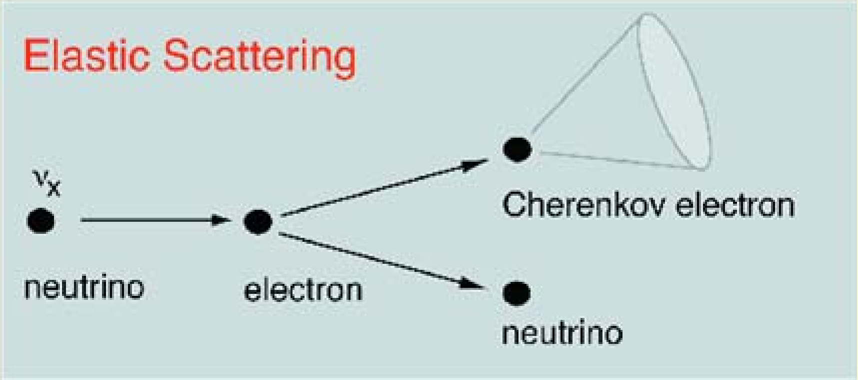


3 ways to detect neutrons

Elastic Scattering (ES)

$\nu_x + e^- \rightarrow \nu_x + e^-$

ν_x, but enhanced for ν_e



Solar Neutrino Physics From SNO

Clear Evidence: Flavor change + active neutrino appearance

June 2001 (with SK)

$$\frac{\Phi_{CC}}{\Phi_{ES}} = \frac{\nu_e}{\nu_e + 0.15\,(\nu_\mu + \nu_\tau)}$$

3.3 σ

April 2002
Sept. 2003
March 2005
With salt in SNO

$$\frac{\Phi_{CC}}{\Phi_{NC}} = \frac{\nu_e}{\nu_e + \nu_\mu + \nu_\tau}$$

5.3 σ

> 7 σ

Total ^{8}B Solar Neutrino Flux

June 2001

$$\Phi_x = \Phi_{CC} + (\Phi_{ES} - \Phi_{CC}) \times (1/0.15)$$

April 2002
Sept. 2003
March 2005

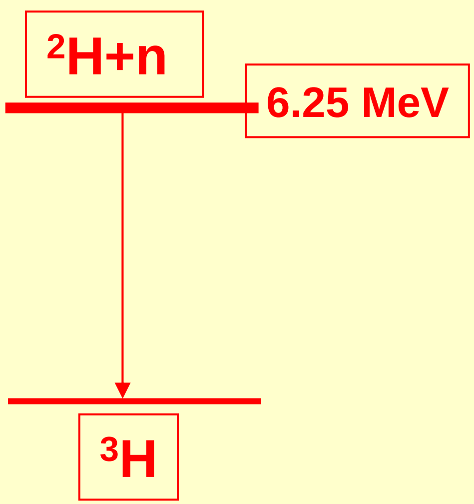
$$\Phi_x = \Phi_{nc}$$

~10%

3 neutron (NC) detection methods (systematically different)

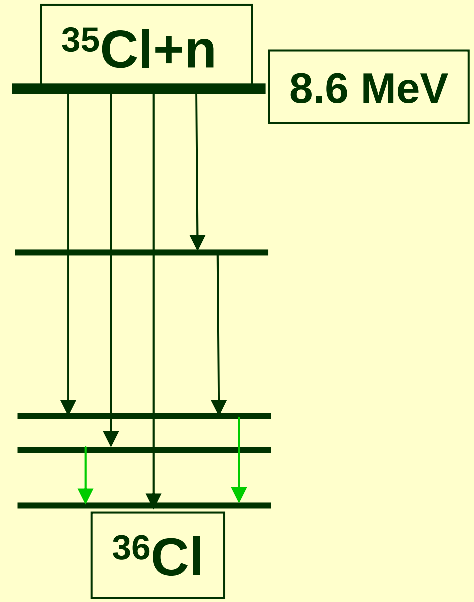
Phase I (D_2O)
Nov. 99 - May 01

n captures on
$^2H(n, \gamma)^3H$
Effc. ~14.4%
NC and CC separation by energy, radial, and directional distributions



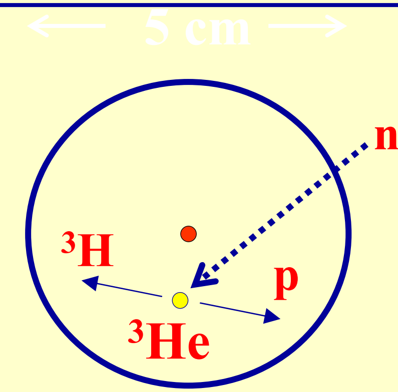
Phase II (salt)
July 01 - Sep. 03

2 t NaCl. n captures on
$^{35}Cl(n, \gamma)^{36}Cl$
Effc. ~40%
NC and CC separation by event isotropy



Phase III (^3He)
Nov. 04-Dec. 06

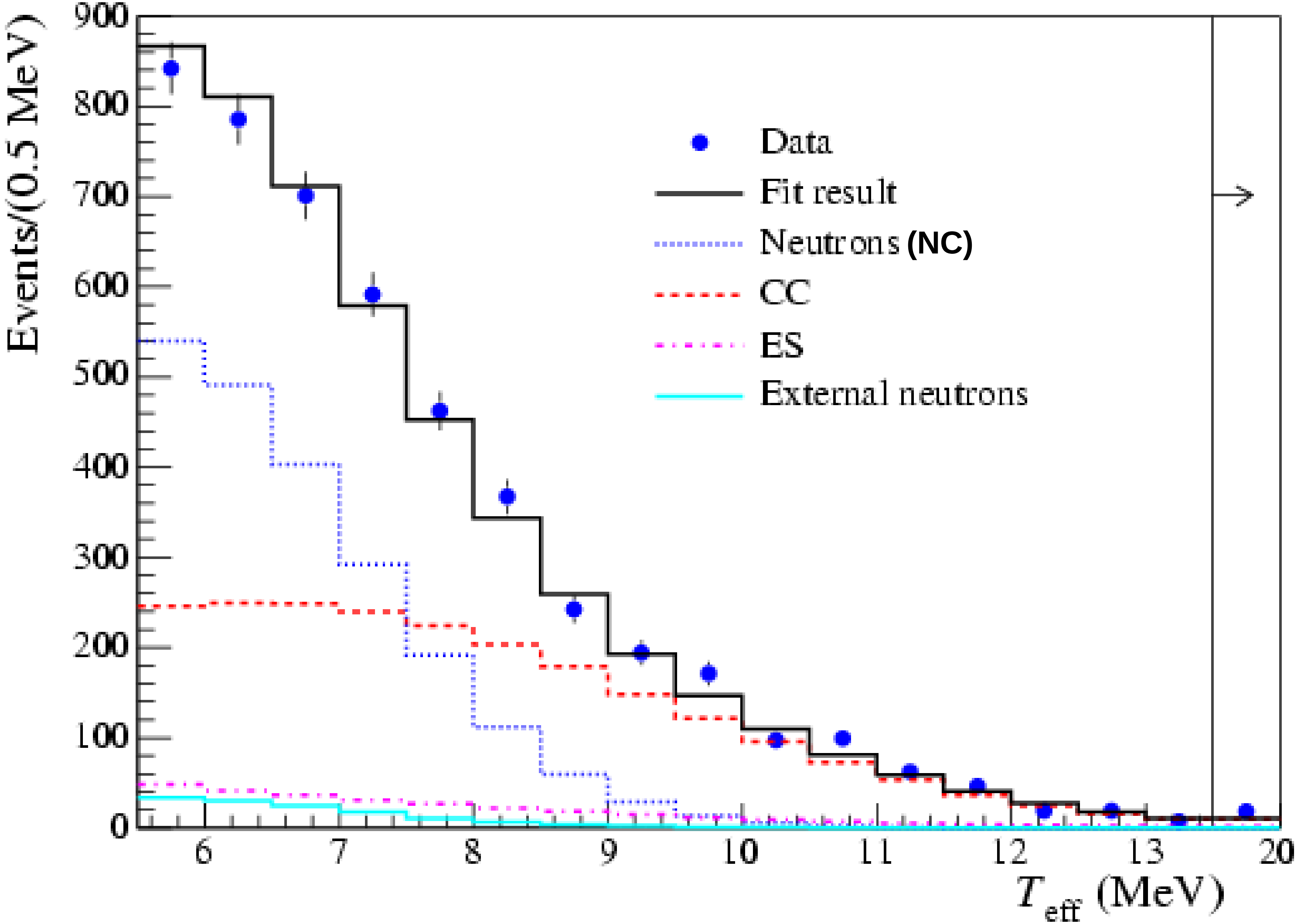
40 proportional counters
$^3He(n, p)^3H$
Effc. ~ 30% capture
Measure NC rate with entirely different detection system.



$$n + {}^3He \rightarrow p + {}^3H$$

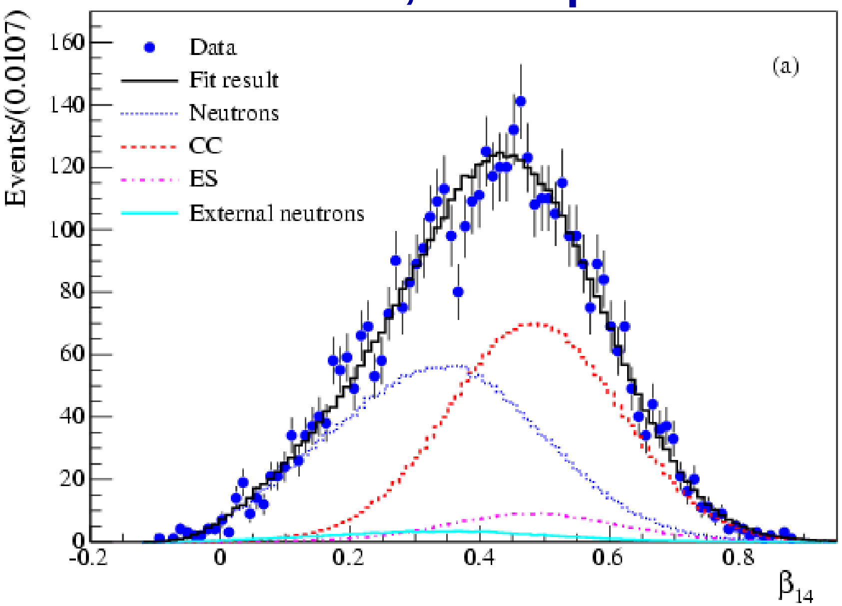
Total Spectrum

"Blind" analysis of data

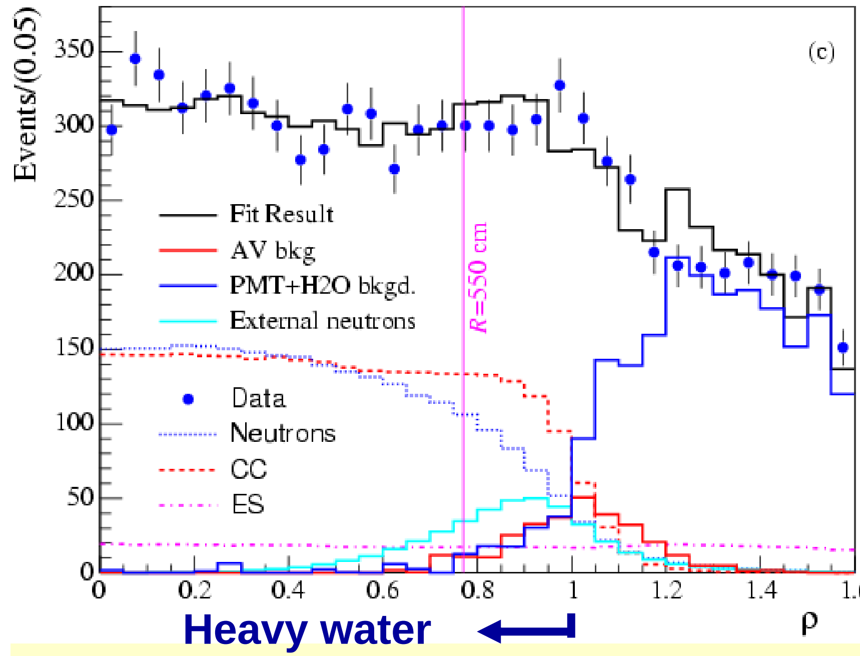


SNO Phase 2 with salt

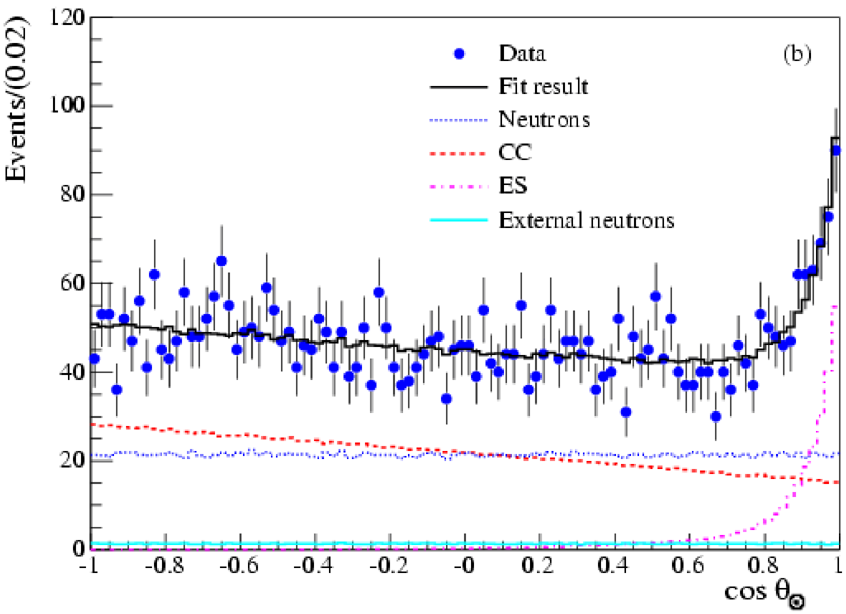
ISOTROPY: NC, CC separation



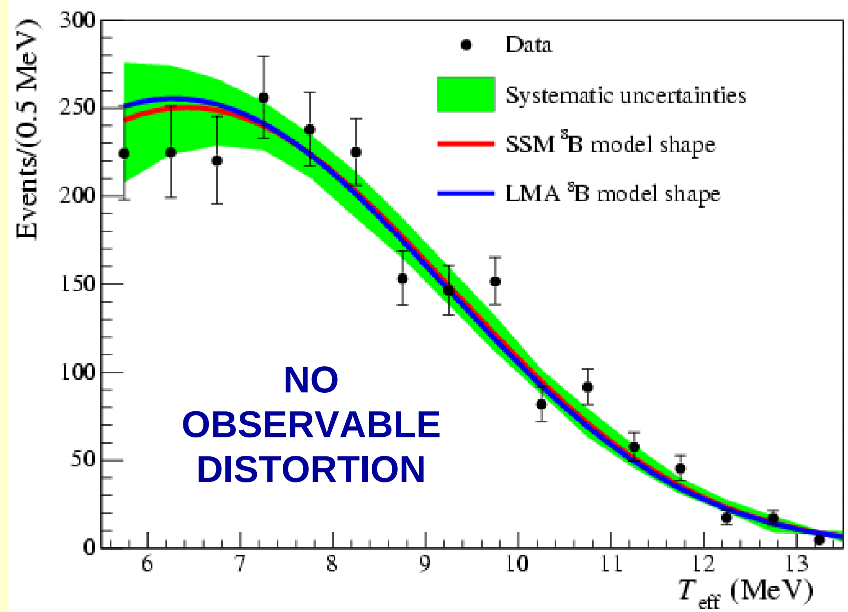
EVENTS VS VOLUME: Bkg < 10%

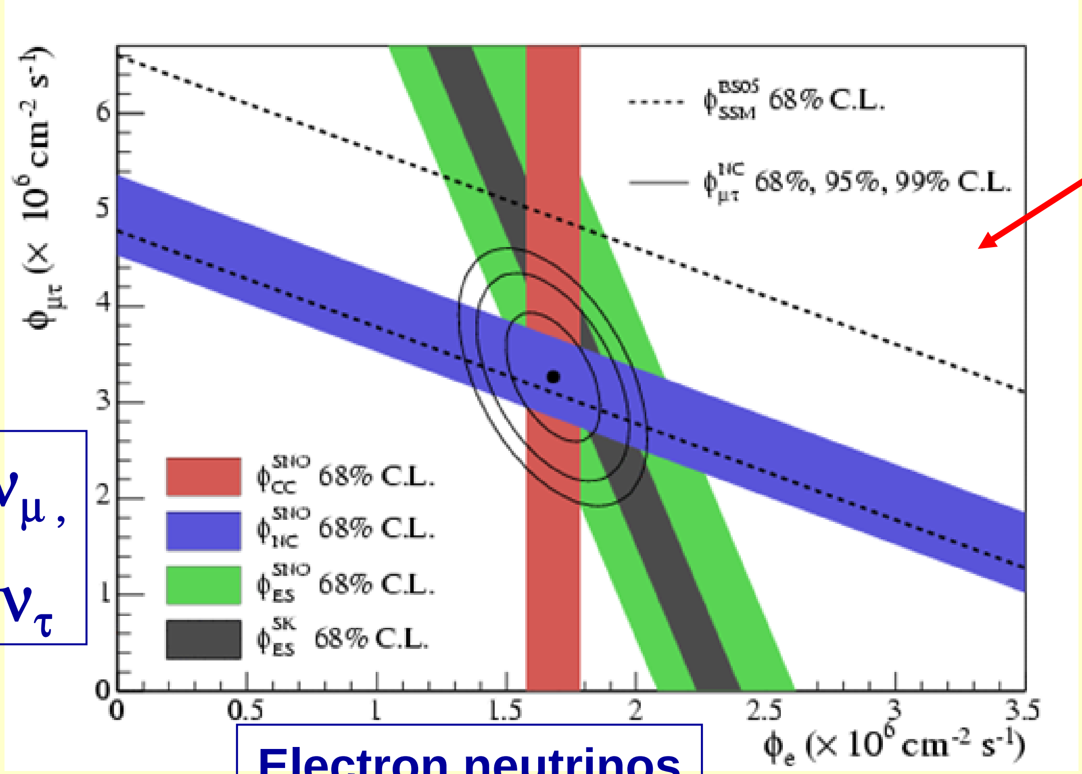


DIRECTION FROM SUN



ENERGY SPECTRUM FROM CC REACTION





ν_μ, ν_τ

Electron neutrinos

Flavor change determined by > 7 σ.

CC, NC FLUXES MEASURED INDEPENDENTLY

The Total Flux of Active Neutrinos is measured independently (NC) and agrees well with solar model Calculations:

5.82 +- 1.3 (Bahcall et al),

5.31 +- 0.6 (Turck-Chieze et al)

$$\phi_{CC} = 1.68 \; {}^{+0.06}_{-0.06}(\text{stat.})^{+0.08}_{-0.09}(\text{syst.})$$

$$\phi_{NC} = 4.94 \; {}^{+0.21}_{-0.21}(\text{stat.})^{+0.38}_{-0.34}(\text{syst.})$$

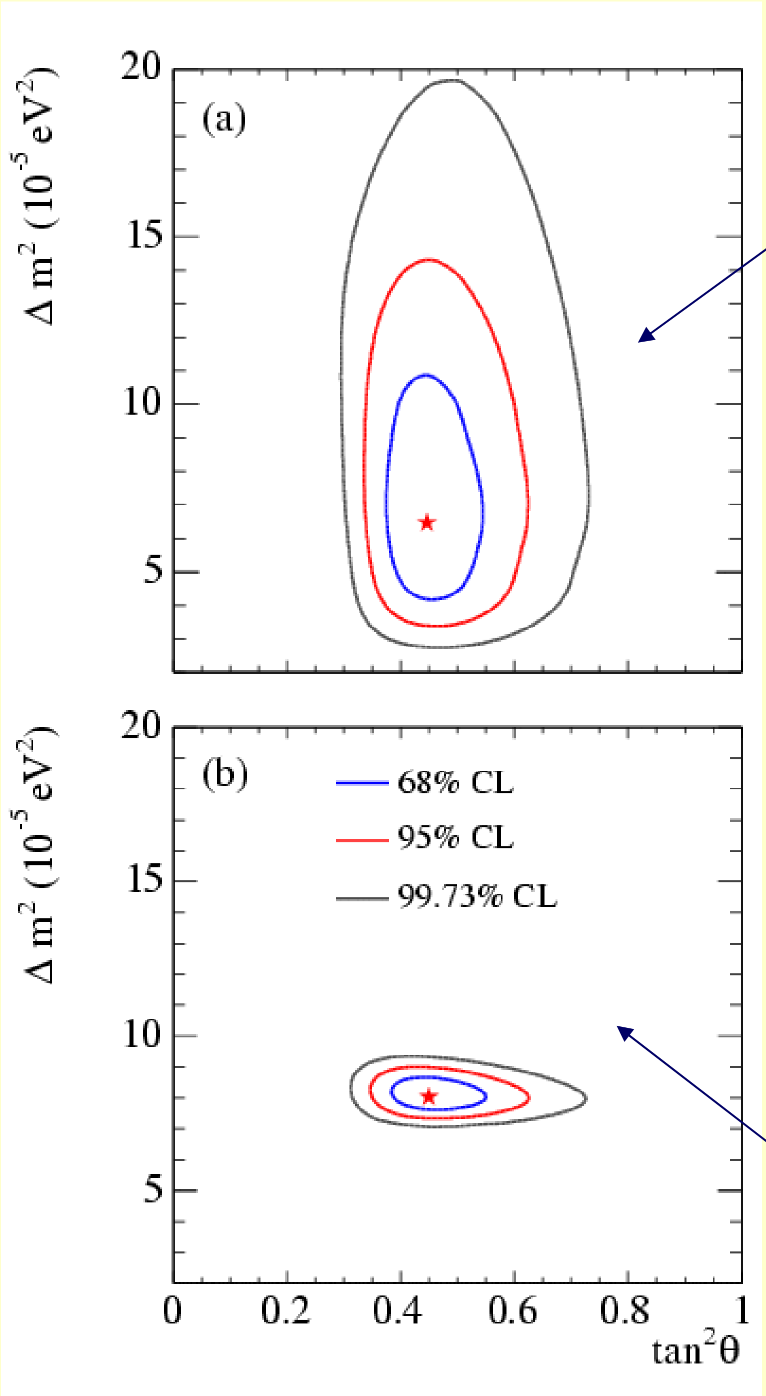
$$\phi_{ES} = 2.35 \; {}^{+0.22}_{-0.22}(\text{stat.})^{+0.15}_{-0.15}(\text{syst.})$$

(In units of $10^6 \text{cm}^{-2}\text{s}^{-1}$)

Test solar physics?: Pena-Garay: Venice07

$$\frac{\phi_{CC}}{\phi_{NC}} = 0.34 \pm 0.023(\text{stat.})^{+0.029}_{-0.031} = \cos^4\theta_{13}\sin^2\theta_{12}$$

Improved accuracy for θ_{12}.



SOLAR ONLY AFTER NEW SNO SALT DATA

- The solar results define the mass hierarchy ($m_2 > m_1$) through the Matter interaction (MSW)

- SNO: CC/NC flux defines $\tan^2\theta < 1$ (ie Non - Maximal mixing) by more than 5 standard deviations

Large mixing Angle (LMA) Region only

LMA for solar ν predicts very small spectral distortion, small (~ 3 %) day-night asymmetry, as observed by SNO, SK

$$Asym_{salt + D_2O} = 0.037 \pm 0.040$$

SOLAR PLUS KAMLAND (assuming CPT) (Reactor $\bar{\nu}$'s)

Periodicity in Solar Flux?

hep-ex/0507079

SNO data 1999-2003

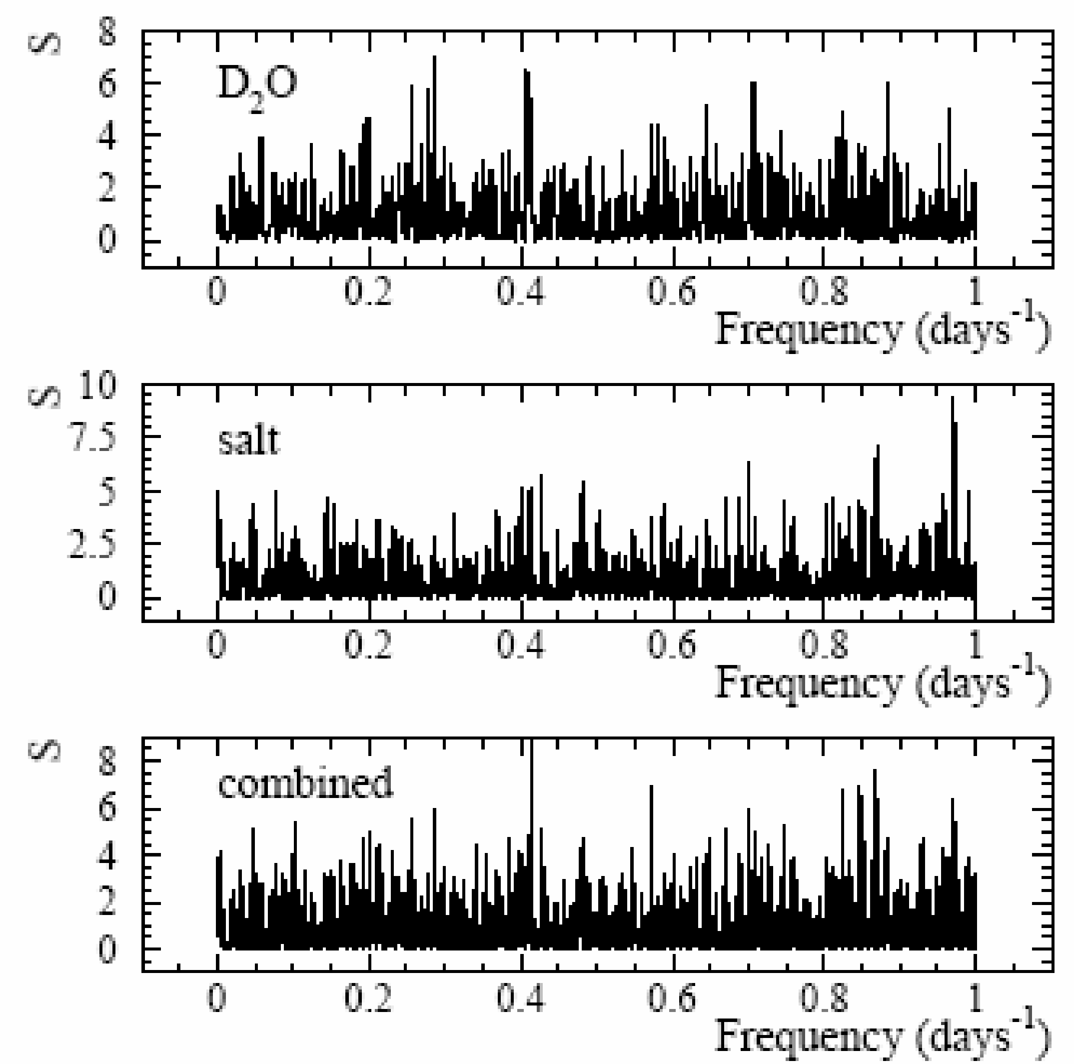


FIG. 2: Likelihood ratio (S) as a function of frequency for the unbinned maximum likelihood method for SNO's D_2O, salt, and combined data sets.

Unbinned Maximum Likelihood Method compares fit for Sinusoidal variation with Expectation for zero amplitude.

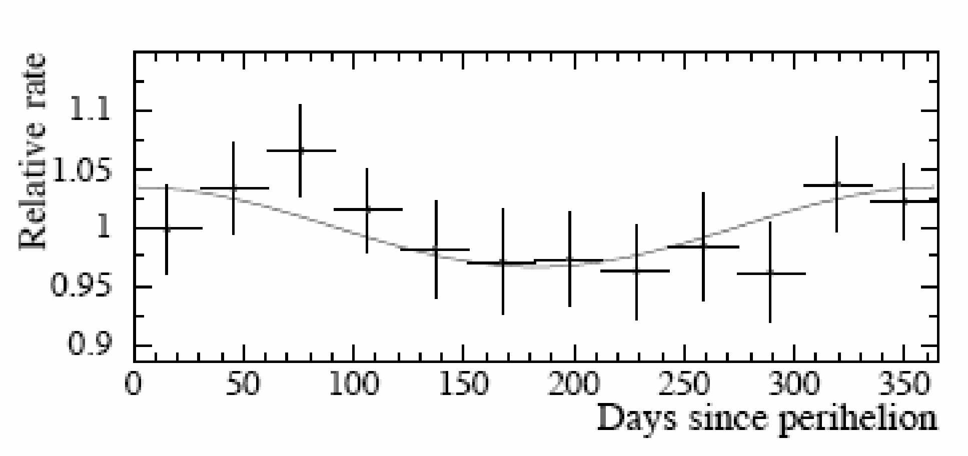
Monte Carlo used to estimate sensitivity shows 35% probability of a larger likelihood ratio (S) with zero sinusoidal amplitude than the maximum S observed in the fits.

Conclusion: No observed sinusoidal variation at periods from 1 day to 10 years.

Analysis sensitive to amplitude of 8-10% at 99% C.L..

Orbital Eccentricity

ε = 0.014(9). Actual: 0.0167



ε = 0.021(3)

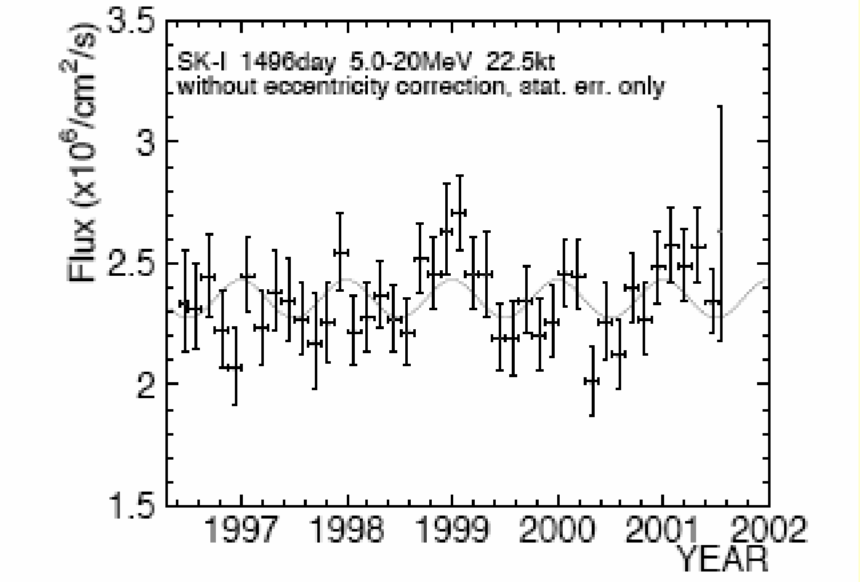
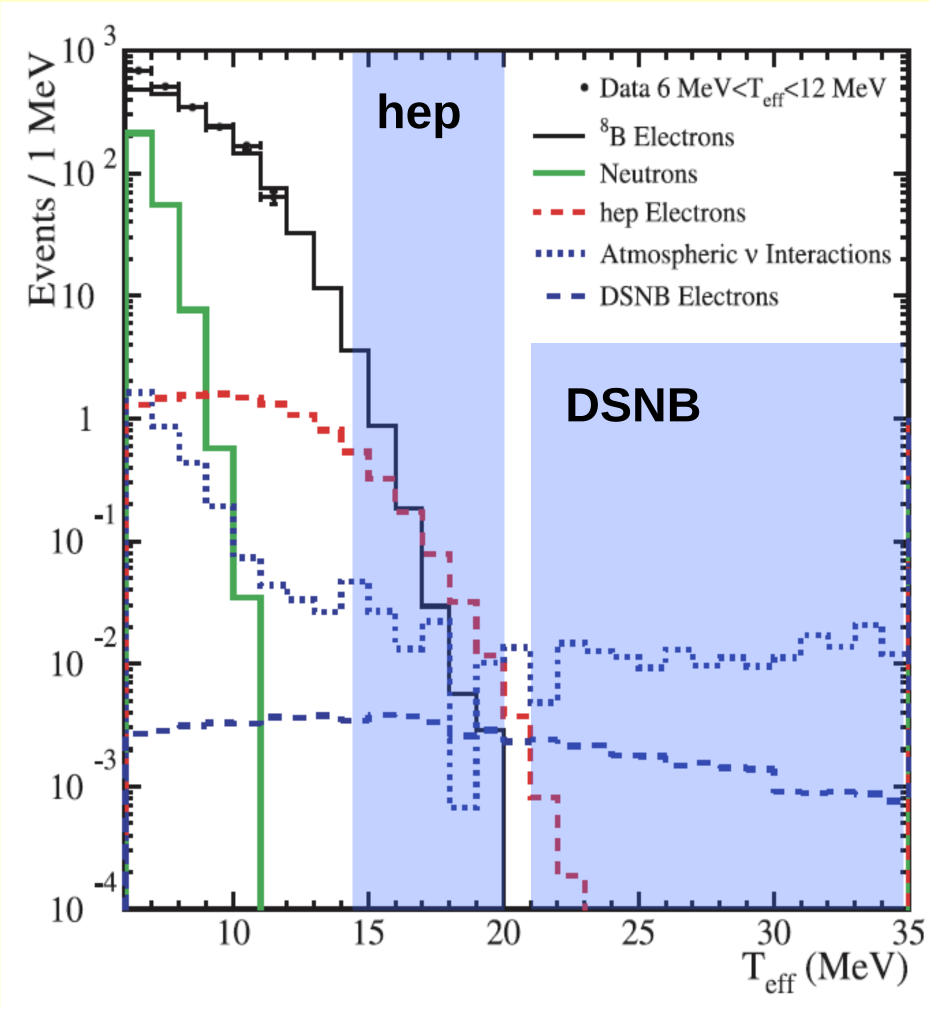


FIG. 42: Solar neutrino flux as a function of time. The binning of the horizontal axis is 1.5 months.

SNO: *hep-ex/0507079*

SK: *hep-ex/0508053*

High(er) energy neutrinos: Solar hep & Diffuse Supernova Neutrino Background (phase I data)



hep **neutrinos** (SSM 8×10^3 $cm^{-2}s^{-1}$)

main background:

^{8}B solar neutrinos

(normalize with low-energy (6-12 MeV) fit, taking into account neutrino oscillations)

2 events observed, consistent with exp. background (3.13±0.60)

$\Phi_{hep} < 2.3 \times 10^4$ cm^{-2} s^{-1}

DSNB elect. neutrinos

main background:

atmospheric neutrinos

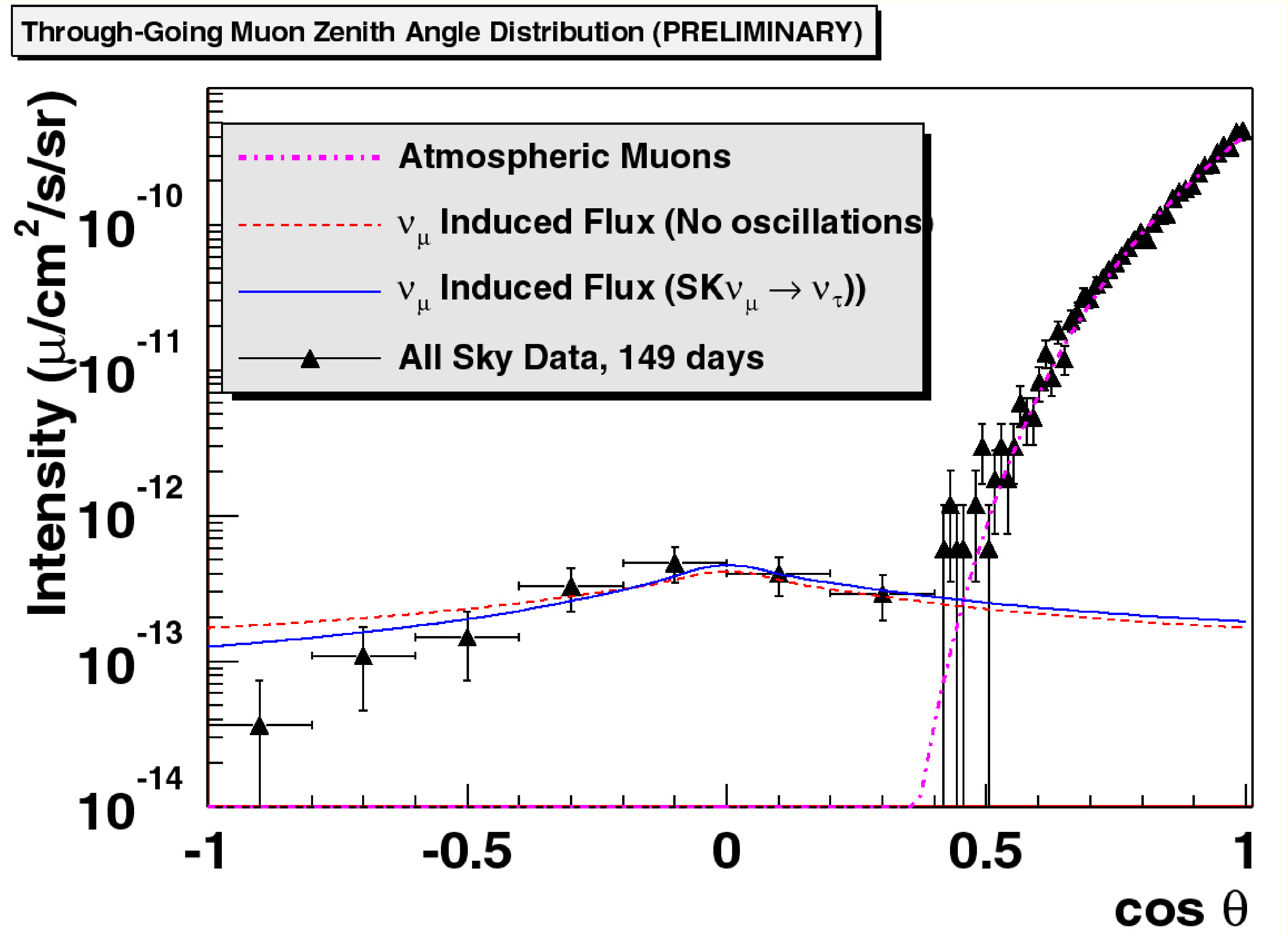
No events observed, consistent with exp. background (0.18±0.04)

$\Phi_{DSNB} < 70$ cm^{-2} s^{-1} (in E window)

Astrophys. J. 653, 1545, 2006

Improves limit on hep by 6.5 and limit on DSNB for electron neutrinos by 100

SNO Muon & Atmospheric Neutrino Analysis



Summary of SNO results

- Direct observation (7 σ) of neutrino flavor change via an appearance measurement:
  Beyond the Standard Model for Elementary Particles.

- Direct measurement (10 % accuracy) of total flux of active neutrinos: Strong confirmation of Solar Models.

- The dominant transformation is to active neutrinos: Sterile neutrino fraction is restricted (<~ 13%).

- Clear determination (5.3 σ): θ_{12} **is non-maximal**.

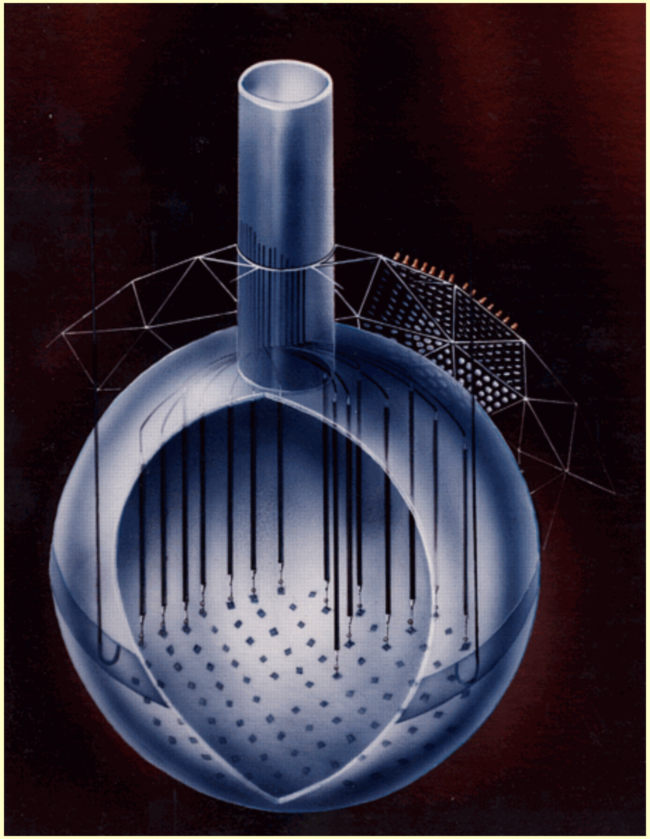
- With other solar measurements: Strong evidence for Matter Enhancement in Sun (MSW – LMA solution).

- With Kamland and CPT: Strong confirmation of neutrino oscillation due to finite mass (MNSP) as the primary physics explanation for appearance and disappearance measurements.

Present Phase: SNO Phase III

Neutral-Current Detectors (NCD):
An array of ^{3}He proportional counters

40 strings on 1-m grid
~440 m total active length



- Search for spectral distortion
- Improve solar neutrino flux by breaking the CC and NC correlation (ρ = -0.53 in Phase II):

CC: Cherenkov Signal ⇒ **PMT Array**

NC: n+^{3}He ⇒ **NCD Array**

- Improvement in θ_{12}, as

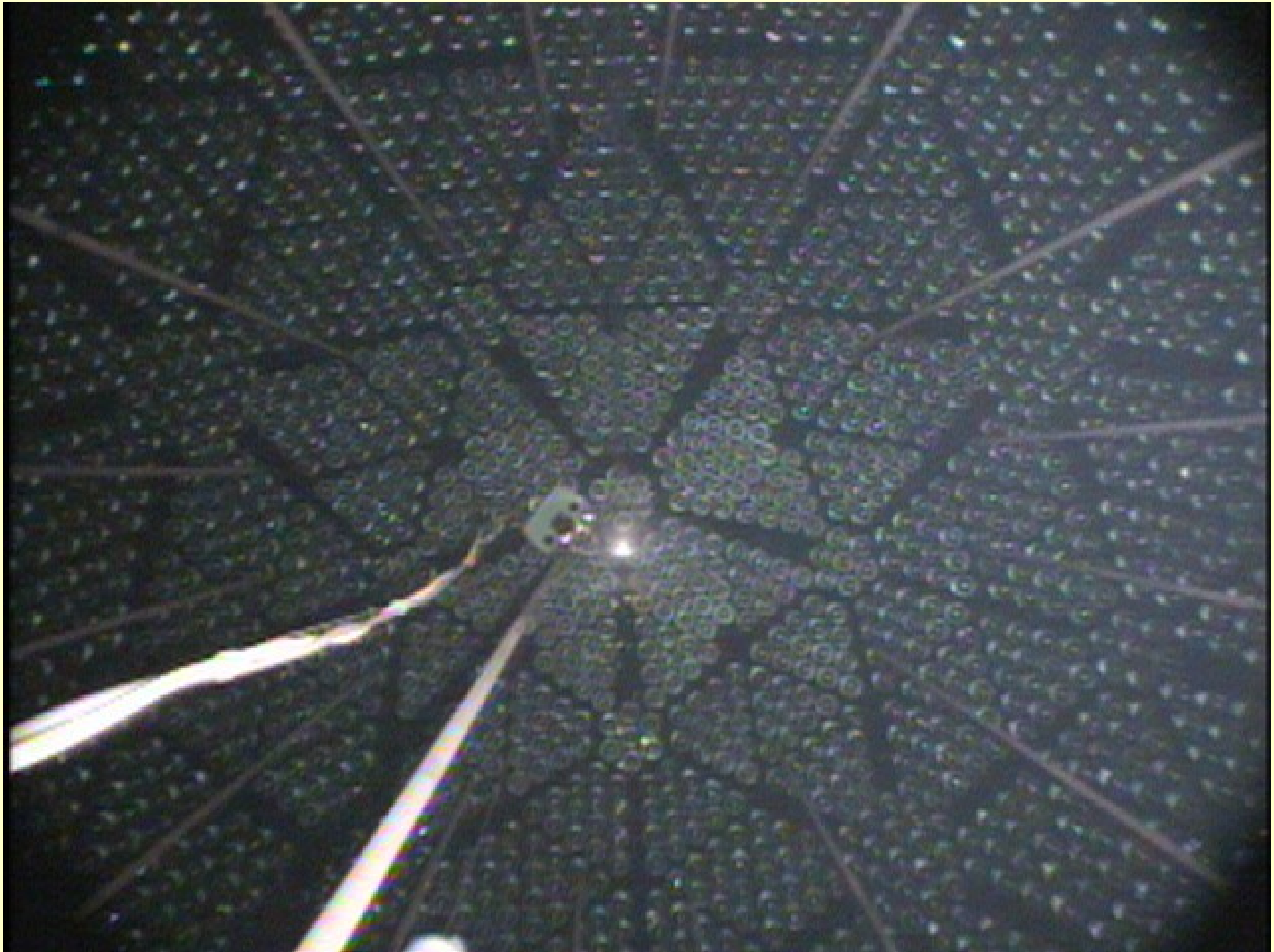
$$\frac{\phi^{CC}}{\phi^{NC}} \approx \sin^4\theta_{13} + \cos^4\theta_{13}\sin^2\theta_{12}$$

Correlations	D_2O unconstrained	D_2O constrained	Salt unconstrained	NCD
NC,CC	-0.950	-0.520	-0.521	~0
CC,ES	-0.208	-0.162	-0.156	~-0.2
ES,NC	-0.297	-0.105	-0.064	~0

Blind Analysis

Phase III production data taking Dec 2004 to Dec 2006. D_2O now removed.

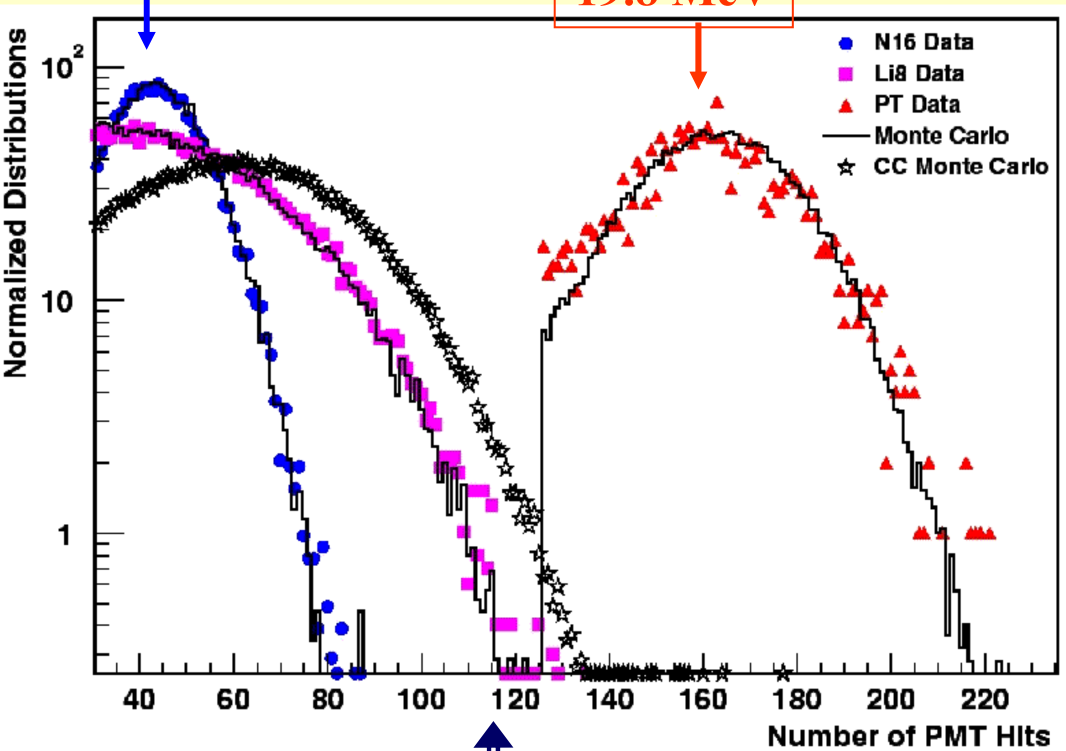
Neutral Current Detector Array deployed and removed using a remotely operated submarine.



SNO Energy Calibrations: 25% of running time

6.13 MeV

19.8 MeV



β's from ^{8}Li

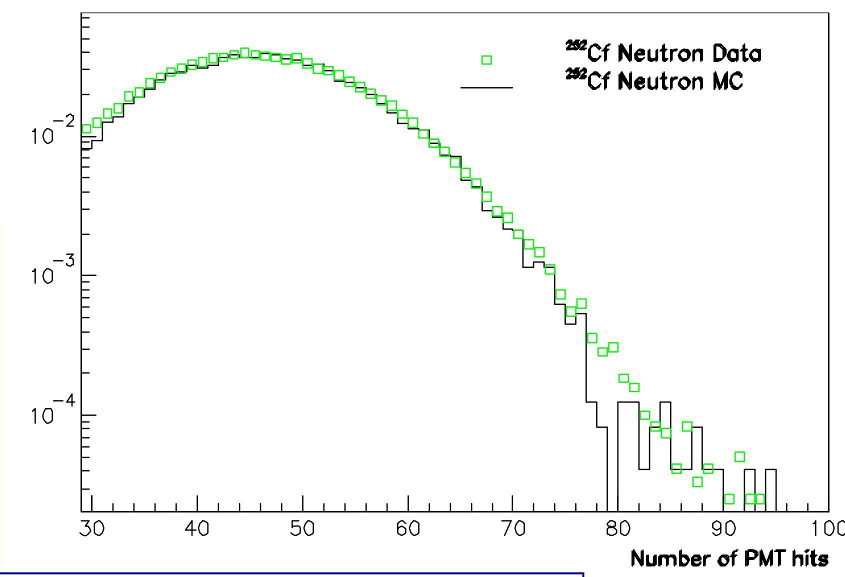
γ's from ^{16}N and t(p,γ)^{4}He

Energy calibrated to ~1.5 %

Throughout detector volume

^{252}Cf neutrons

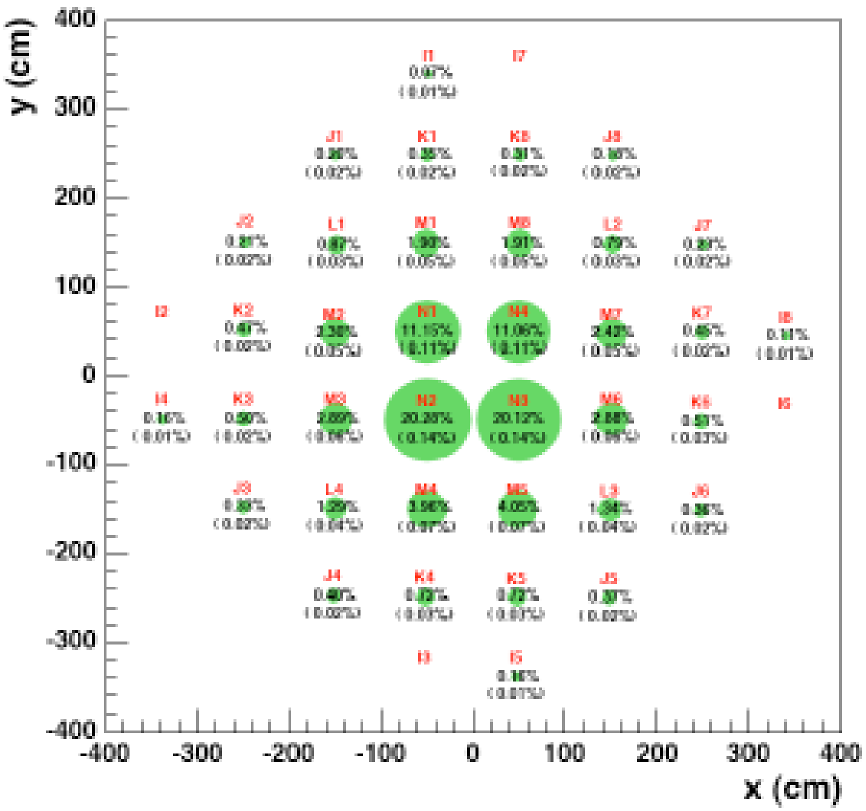
+ AmBe, ^{24}Na

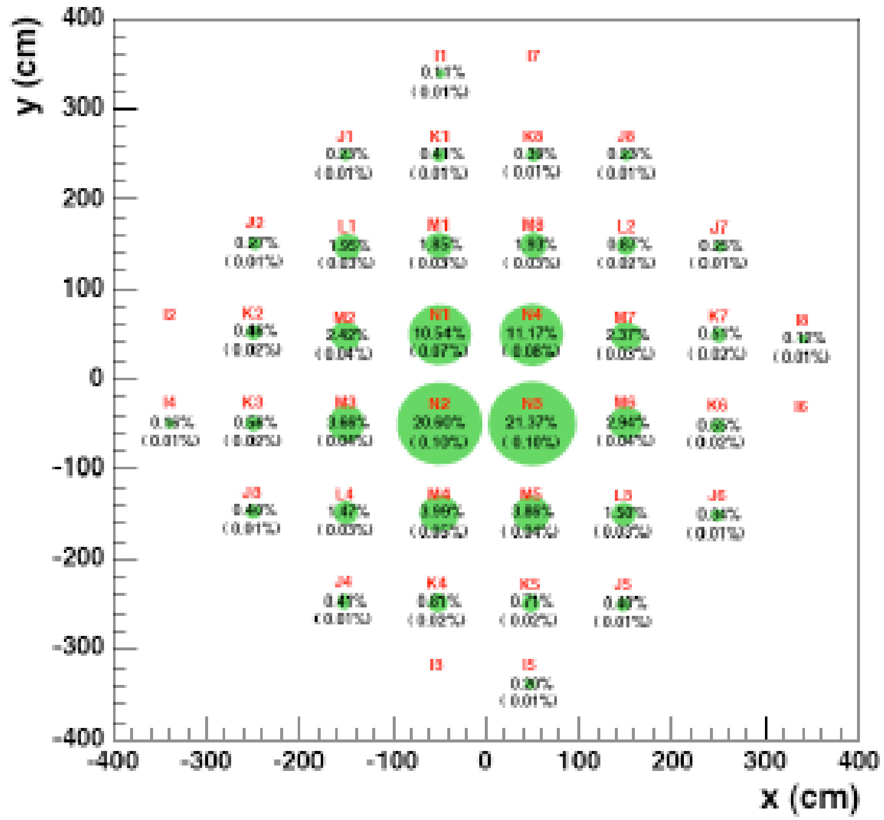


Optical calibration at 5 wavelengths with the "Laserball"

Neutron Efficiency

- Comparison of the MC prediction and ADC data (Cf source):

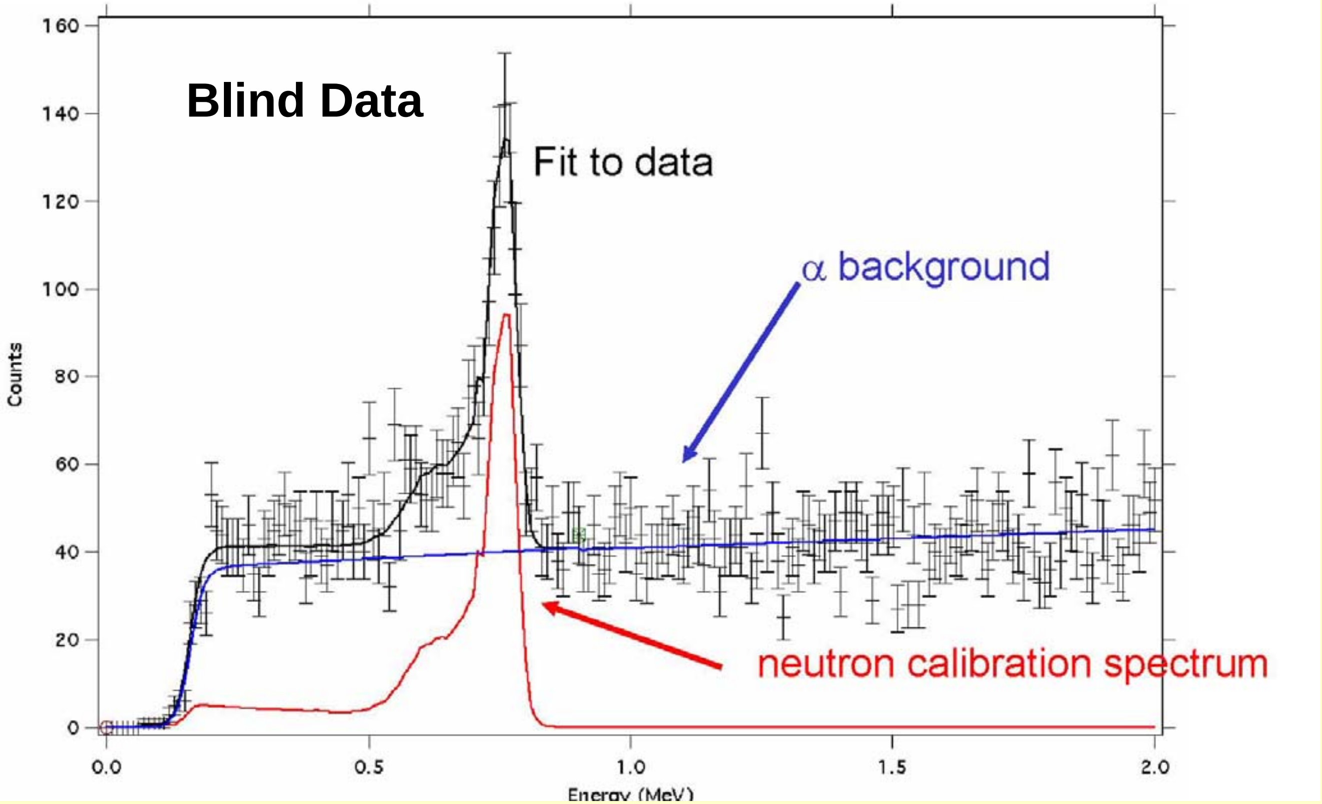




SNO NCD Signals

$n + {}^3He \rightarrow p + {}^3H \quad (q=768\ keV)$

Pulse shape analysis to discriminate neutrons and alphas underway



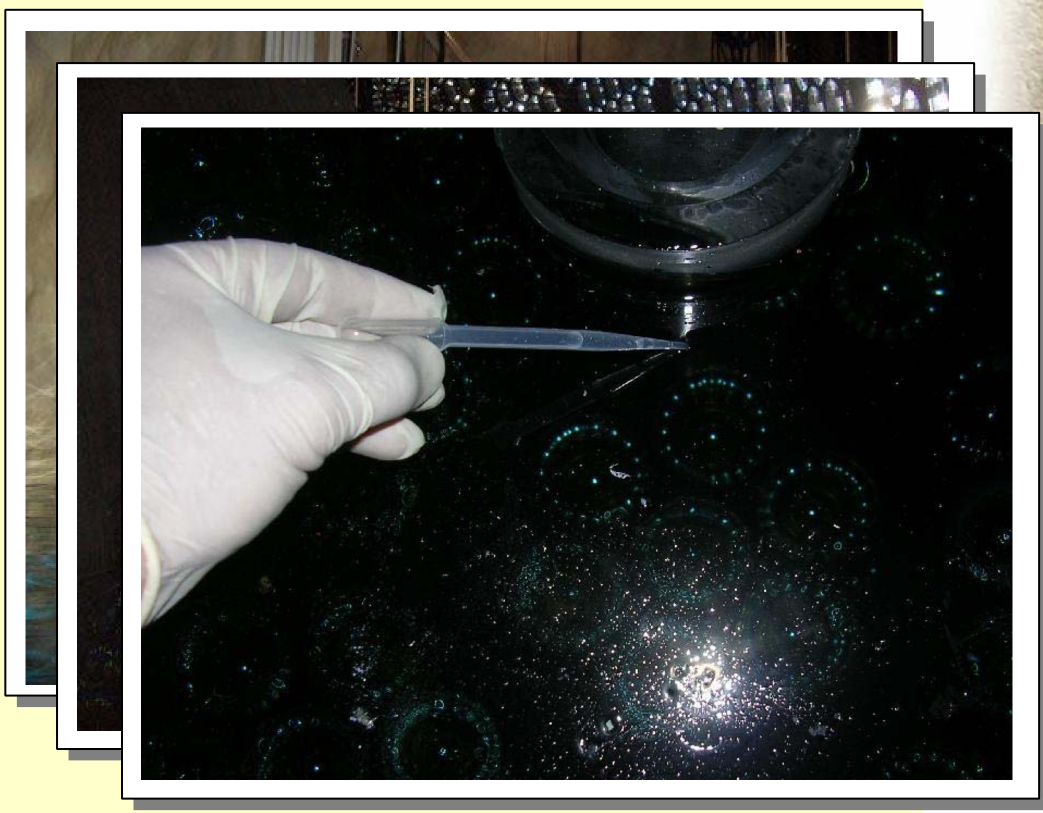
Another analysis is almost complete that combines data from the first two SNO Phases and reduces the threshold by ~ 1 MeV.

This also provides improved accuracy on CC/NC flux ratio and therefore θ_{12} mixing matrix element.

Very low Background. About one count per 2 hours in region of interest.
Can be reduced by a factor of more than 20 by pulse shape discrimination.

SNO

- Ended data taking 28 Nov 2006
- All heavy water removed by June 2007
- Finish desalination of 20 tonnes; end of 2007



Last drop of heavy water being removed: June 2007

SNO Physics Program

- Solar Neutrinos (5 papers to date)
  - → Electron Neutrino Flux
  - → Total Neutrino Flux
  - → Electron Neutrino Energy Spectrum Distortion
  - → Day/Night effects
  - → hep neutrinos hep-ex 0607010
  - → Periodic variations hep-ex/0507079 [Variations < 8% (1 dy to 10 yrs)]
- Atmospheric Neutrinos & Muons
  - → Downward going cosmic muon flux
  - → Atmospheric neutrinos: wide angular dependence [Look above horizon]
- Supernova Watch (SNEWS)
- Limit for Solar Electron Antineutrinos

  hep-ex/0407029
- Nucleon decay ("Invisible" Modes: N → ννν)

  Phys.Rev.Lett. 92 (2004) [Improve limits by 1000]
- Supernova Relic Electron Neutrinos hep-ex 0607010

New International Underground Science Facility At the Sudbury site: SNOLAB

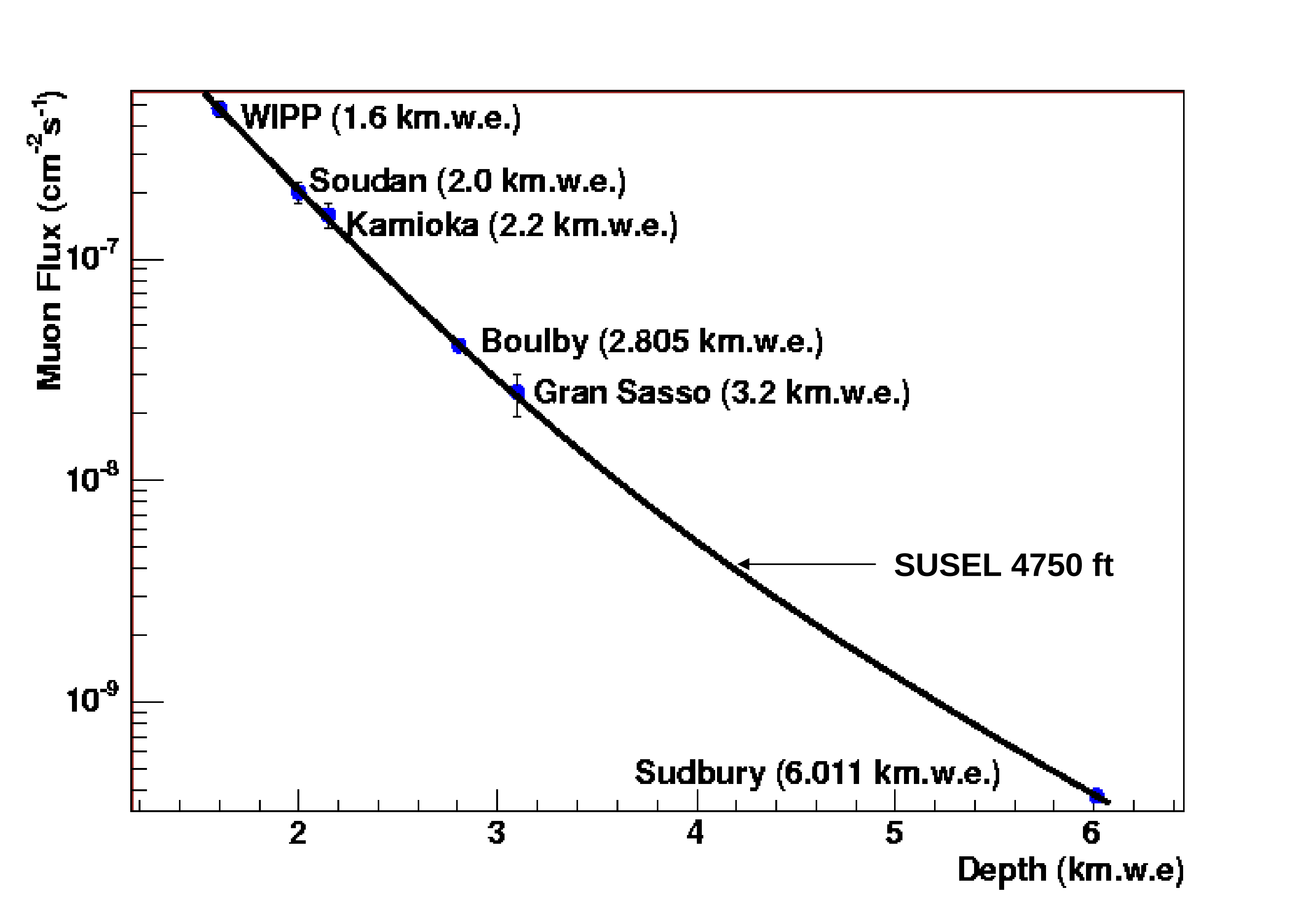
- Underground Laboratory (2 km deep) ($ 38M): Phase 1 Experiments: 2008
- Surface Laboratory ($ 10 M) funded: Complete September, 2005
- Cryopit addition underground: Funding recently completed ($ 15 M)
  Excavation to be completed in 2008

Total additional excavated volume in new lab: 3 times SNO volume.

To pursue Experiments that benefit from a very deep and clean lab:

- Direct Observation of Dark Matter (WIMPS) via nuclear recoil
- Neutrino-less Double Beta Decay
- Low Energy Solar Neutrinos
  - Particle physics and solar physics
- Geo – neutrinos
- Supernova Neutrinos
- Reactor Neutrinos

Total Muon Flux vs Depth Relative to Flat Overburden



Hime - Mei

SNOLAB (Same depth as SNO: 2 km)

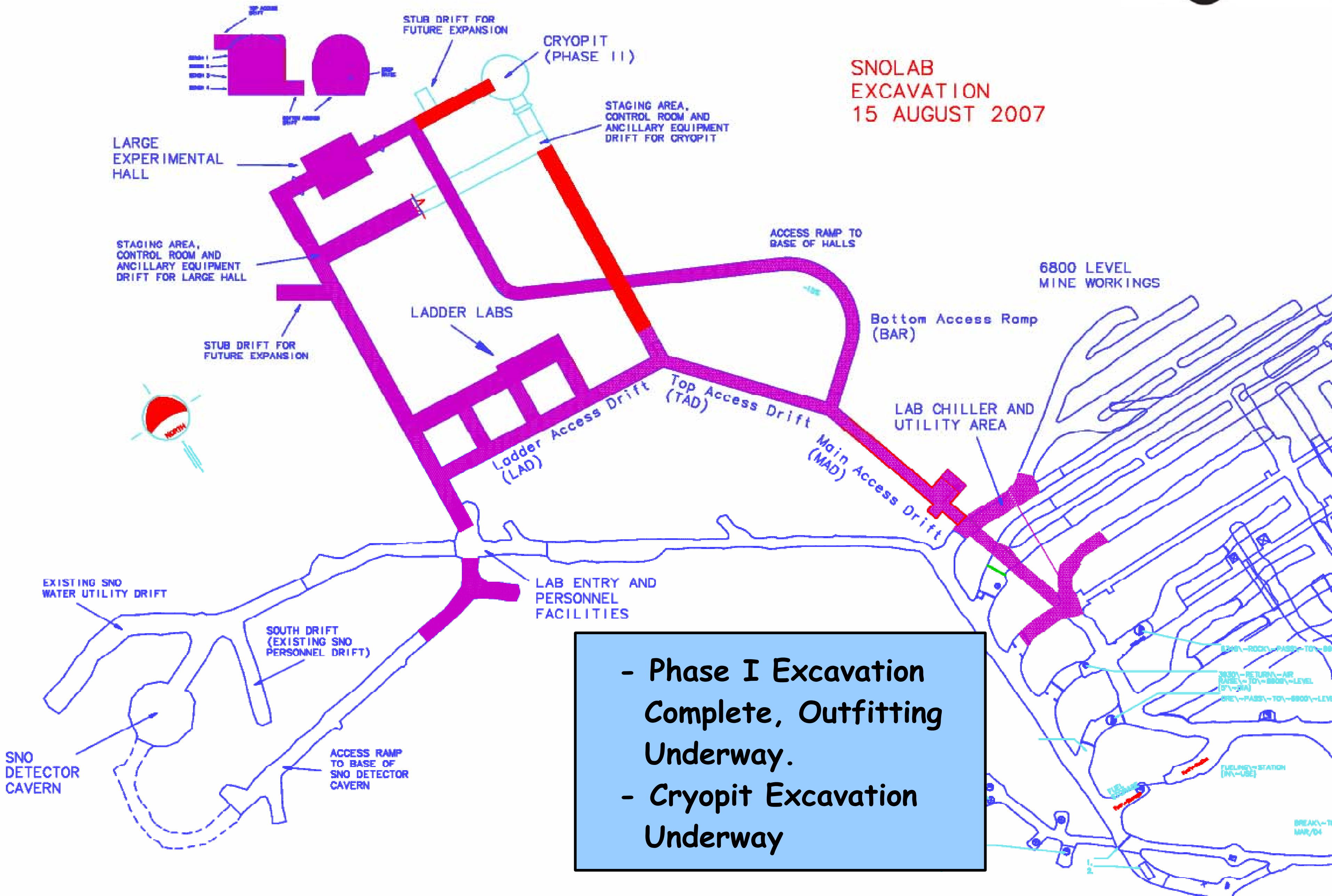
40 to 400 times lower

μ fluxes than

Gran Sasso, Kamioka.

All Lab Air: Class < 2000

Excavation Status



- Phase I Excavation Complete, Outfitting Underway.
- Cryopit Excavation Underway


LADDER
LABS


CUBE
HALL

Letters of Interest for SNOLAB

6 th Workshop and
Experiment Review Committee
Aug 22, 23, 2007
www.snolab.ca

Dark Matter:

Timing of Liquid Argon/Neon Scintillation: DEAP/CLEAN (1 Tonne)

Freon Super-saturated Gel: PICASSO

Silicon Bolometers: SUPER-CDMS

Neutrino-less Double Beta Decay:

^{150}Nd: Organo-metallic in liquid scintillator in SNO+

^{76}Ge: MAJORANA or next generation GERDA/MAJORANA (Longer Term)

^{136}Xe: EXO (Gas or Liquid) (Longer Term)

CdTe: COBRA (Longer Term)

Solar Neutrinos:

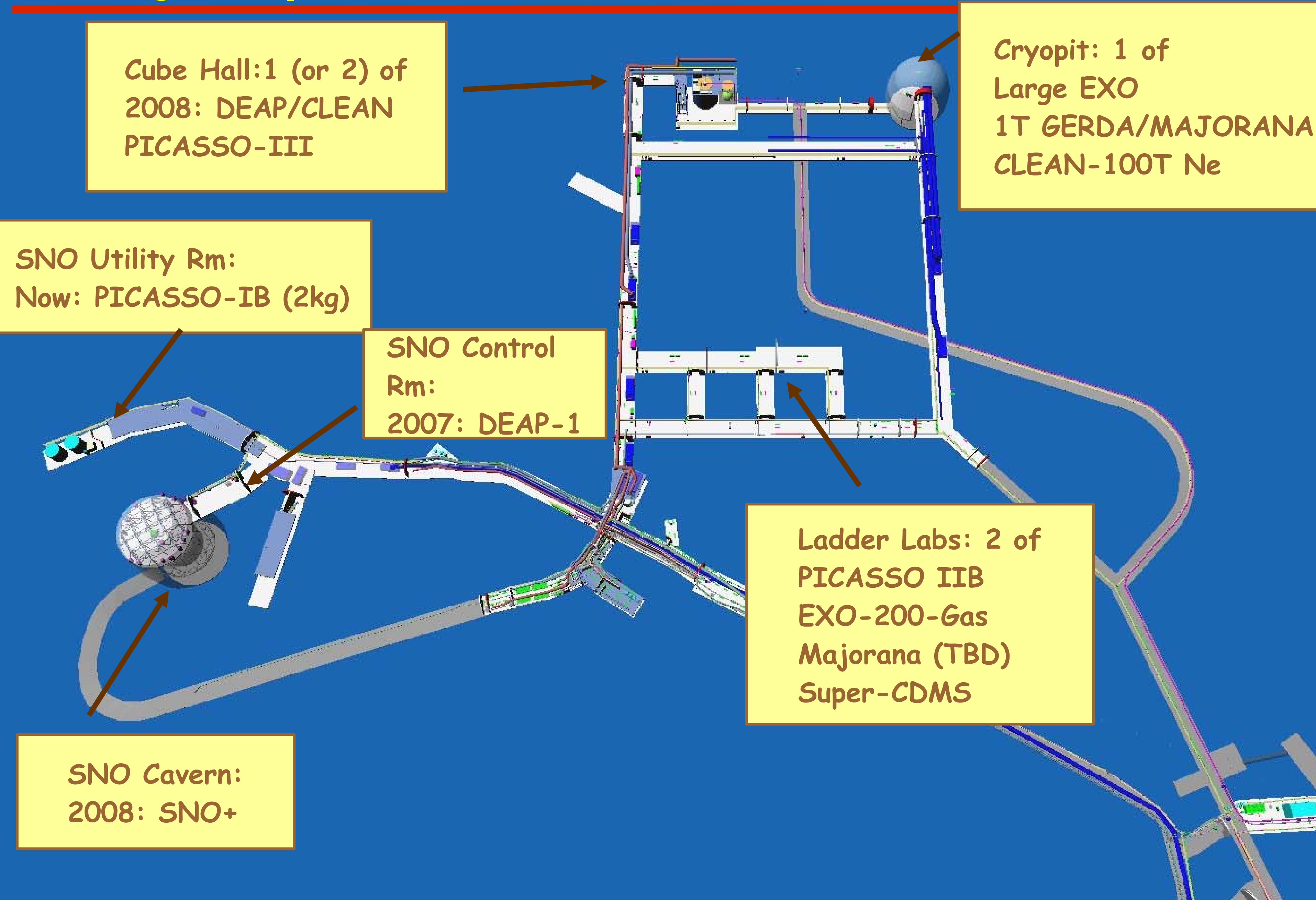
Liquid Scintillator: SNO+ (also Reactor Neutrinos, Geo-neutrinos)

Liquid Ne: CLEAN (also Dark Matter) (Longer Term)

SuperNovae:

SNO+: Liquid scintillator;HALO: Pb plus SNO ^{3}He detectors.

Siting Experiments at SNOLAB



SNO+ Fill SNO with Liquid Scintillator (+ ^{150}Nd)

- SNO plus liquid scintillator → physics program
  - double beta decay (e.g. ^{150}Nd)
  - *pep* and CNO low energy solar neutrinos:
    - pep tests the neutrino-matter interaction, sensitive to new physics
  - geo-antineutrinos (higher flux, lower reactor and radioactive background than Kamland)
  - 240 km baseline reactor oscillation confirmation
  - supernova neutrinos

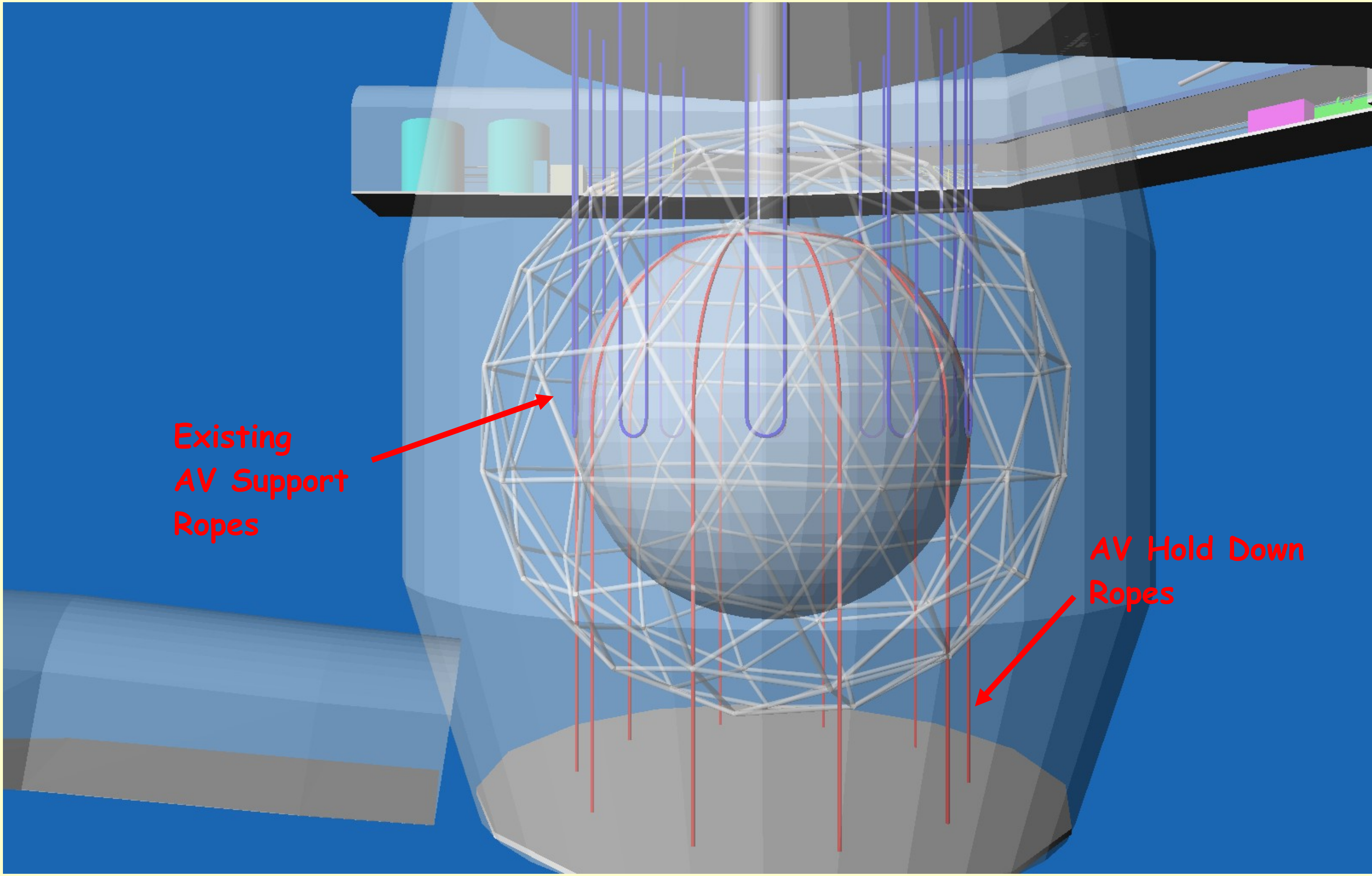
- Technical questions:

- Solved: Linear Alkyl Benzene (LAB) Scintillator: high light output, low effects on acrylic

- Mechanical effects of lower scintillator density: Holddown required for acrylic vessel.

- Radioactive purity of scintillator. In progress.

SNO+

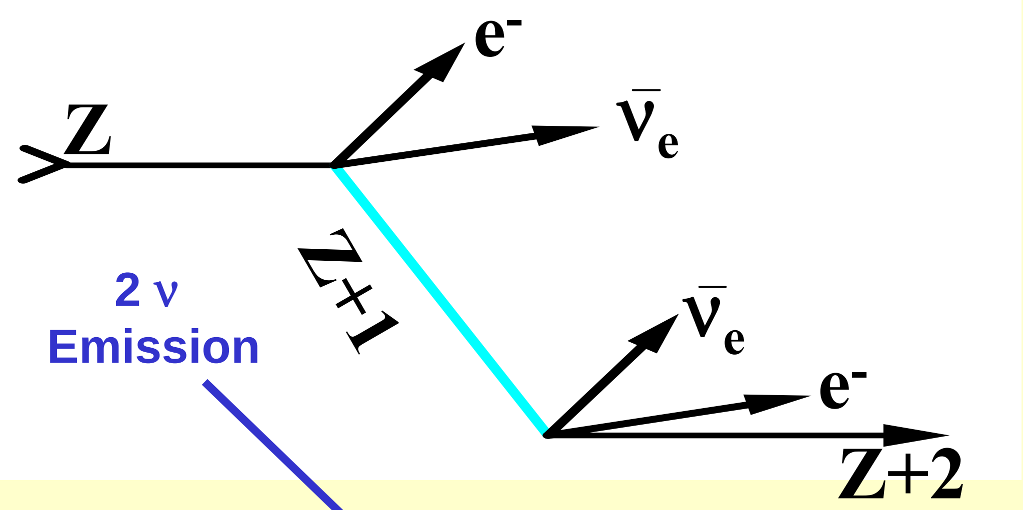


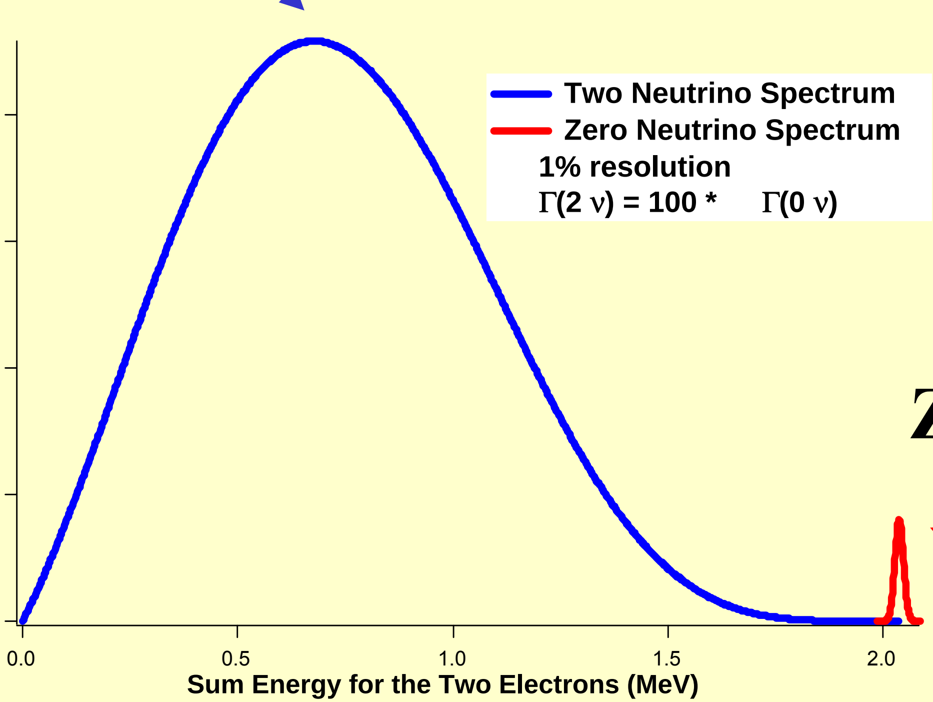
Neutrinoless Double β Decay

Requires:

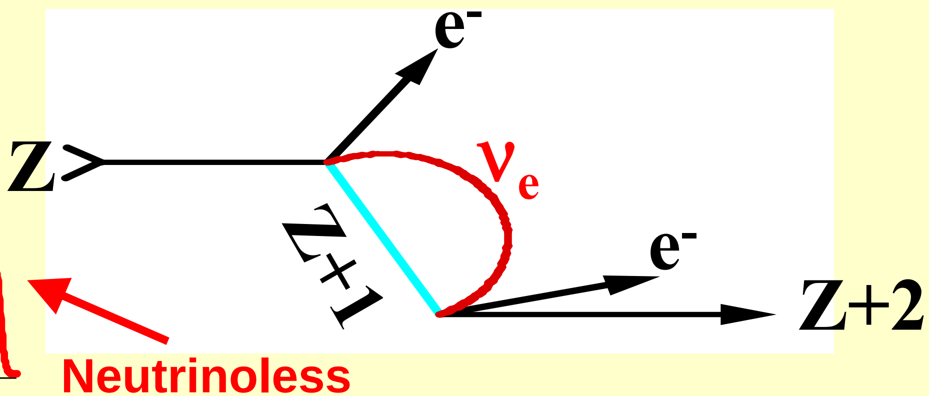
- **Neutrino = Anti-neutrino (Majorana particles)**
- **Finite ν mass**
- **Lifetimes > ~10^{26} years**

Imply ν mass < 0.1 eV





Summed Electron Energy

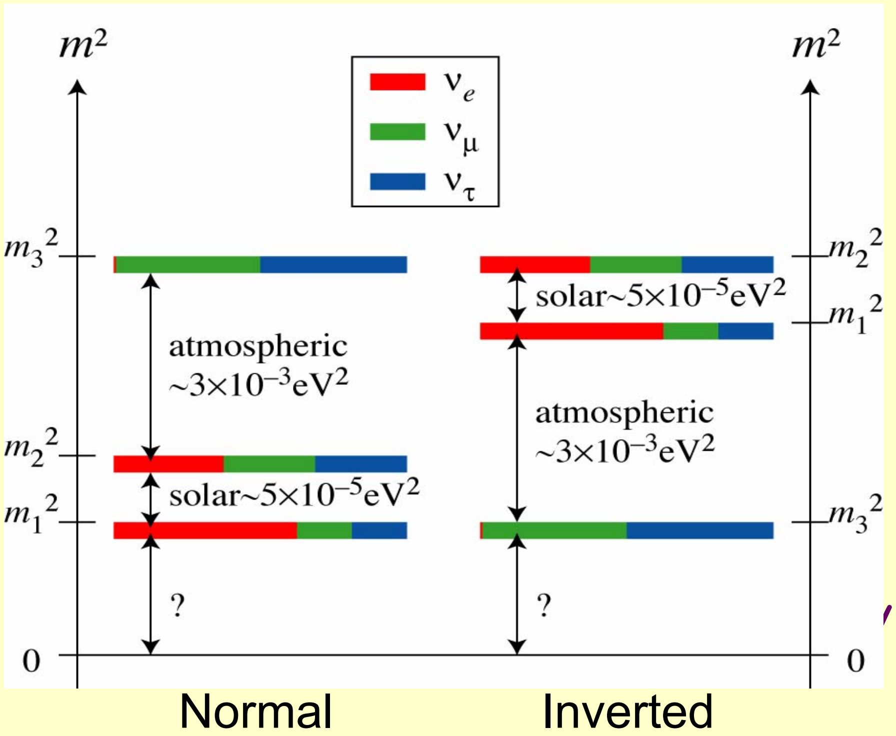


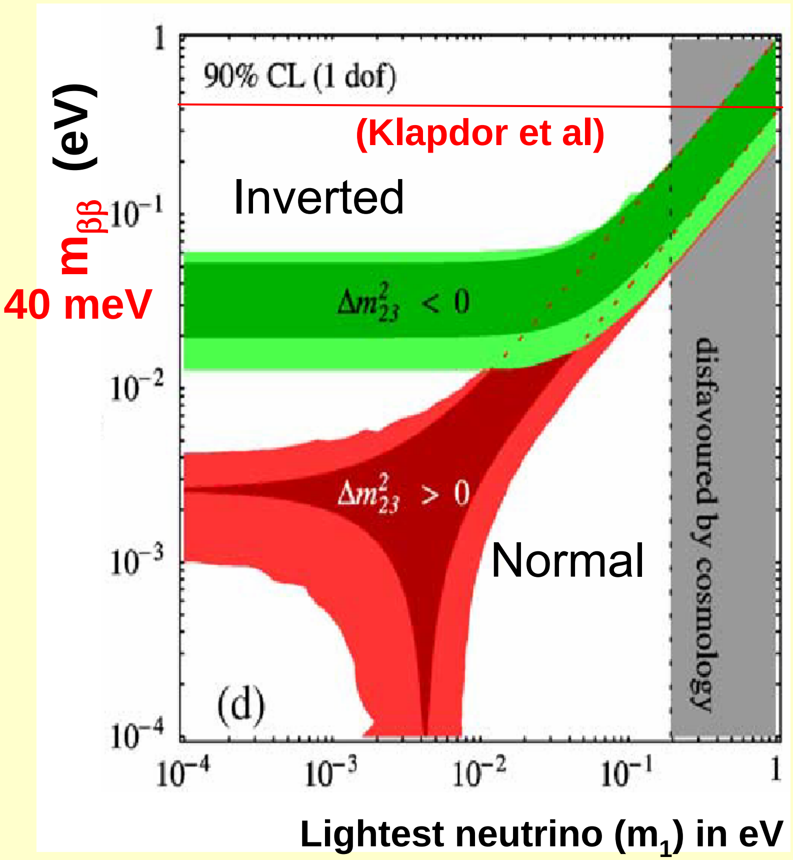
Measuring Effective Mass

$$m_{\beta\beta} = |\sum_i U_{ei}{}^2 m_i|$$

$$m_{\beta\beta} = |m_1 \cos^2\theta_{13}\cos^2\theta_{12} + m_2 e^{2i\alpha} \cos^2\theta_{13}\sin^2\theta_{12} + m_3 e^{2i\beta} \sin^2\theta_{13}|$$

Mass Hierarchies





Want sensitivity <~ 0.15 eV

large mass/low background

SNO+: Neutrino-less Double Beta Decay Candidate

^{150}Nd

- 3.37 MeV endpoint
- isotopic abundance 5.6% (in SNO+ 0.1% loading=56 kg)
- Nd is one of the most favorable double beta decay candidates with large phase space due to high endpoint.
- Nd metallic-organic compound has been demonstrated to have long attenuation lengths, stable for more than a year.
- 0.1 % of Nd can be added with little degradation of light output.
- Ideal scintillator (Linear Alkyl Benzene) has been identified. More light output than Kamland, Borexino, no effect on acrylic.
- Financial support has been obtained for development of a capital proposal

table from F. Avignone Neutrino 2004

$$\overline{\eta} \equiv \langle G^{0\nu} |\mathcal{M}^{0\nu}|^2 \rangle \times 10^{13}$$

Isotope	$\overline{\eta}$
^{48}Ca	0.54
→ ^{76}Ge	0.73
^{82}Se	1.70
^{100}Mo	10.0
^{116}Cd	1.30
→ ^{130}Te	4.20
→ ^{136}Xe	0.28
^{150}Nd	57.0

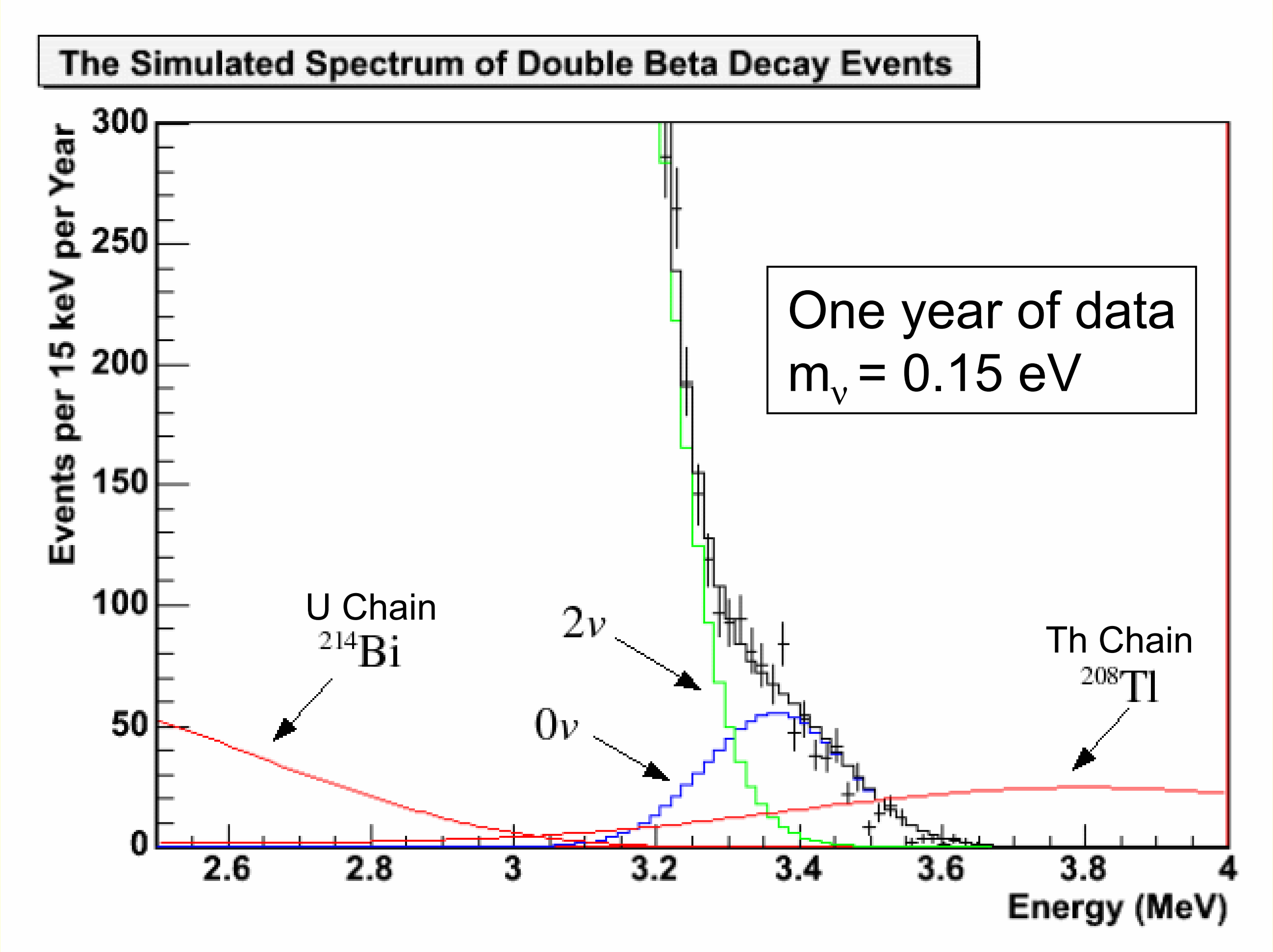
(Within a factor of 2 of recent revised Rodin et al value for Nd)

GERDA (Ge), CUORE (Te), EXO (Xe), are all in progress at ~ 100 kg, with capability < ~ 150 meV for m_ν.

SNO+ (^{150}Nd Neutrino-less Double Beta Decay)

0ν: 1057 events per year with 500 kg ^{150}Nd-loaded liquid scintillator in SNO+.

Simulation assuming light output and background similar to Kamland.

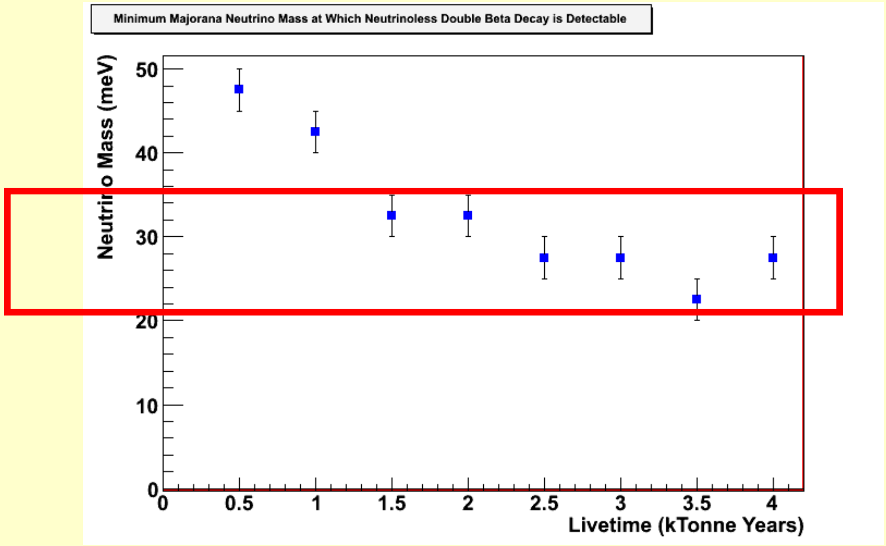


Super-Nemo and SNO+ seek use of Laser Isotope Separation facility in France to enrich 100's of kg of ^{150}Nd isotope. CEA has agreed to initial study during 07/08

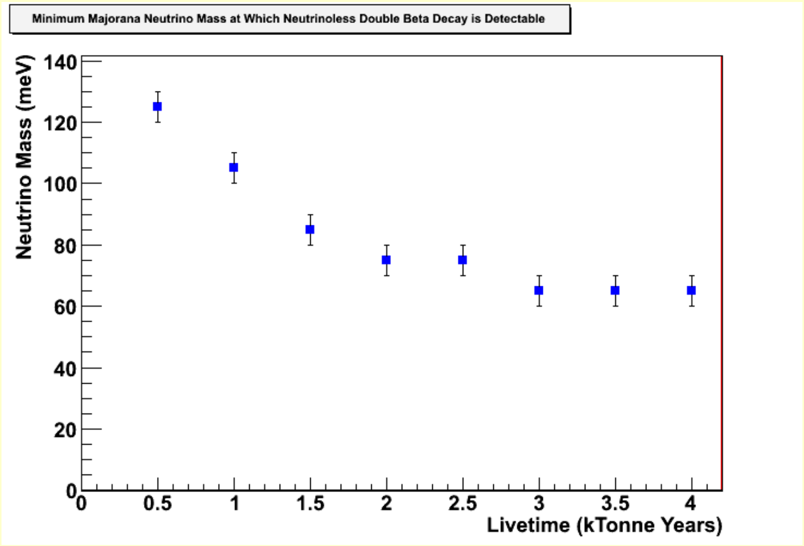
Neutrino Mass Sensitivity in SNO+

corresponds to 0.1% natural Nd LS in SNO+

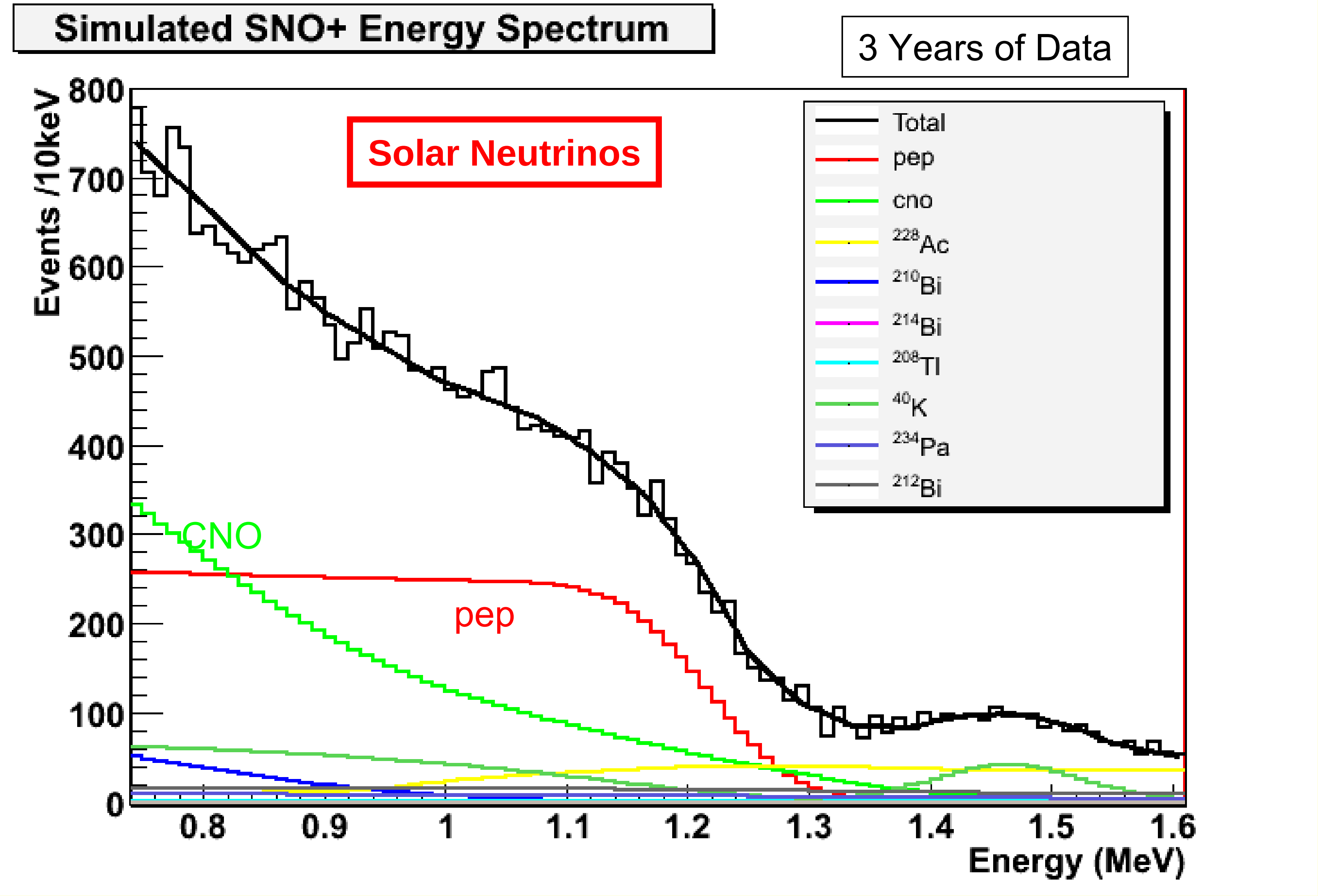
500 kg isotope



56 kg isotope



- 3 sigma detection on at least 5 out of 10 fake data sets
- 2ν/0ν decay rates are from Elliott & Vogel, Ann. Rev. Nucl. Part. Sci. **52**, 115 (2002)



Backgrounds assumed at Kamland observed values plus their purification objectives for ^{210}Bi, ^{40}K. Negligible background from ^{11}C at SNOLAB depth.

Survival Probability Rise

SSM pep flux:

uncertainty ±1.5%

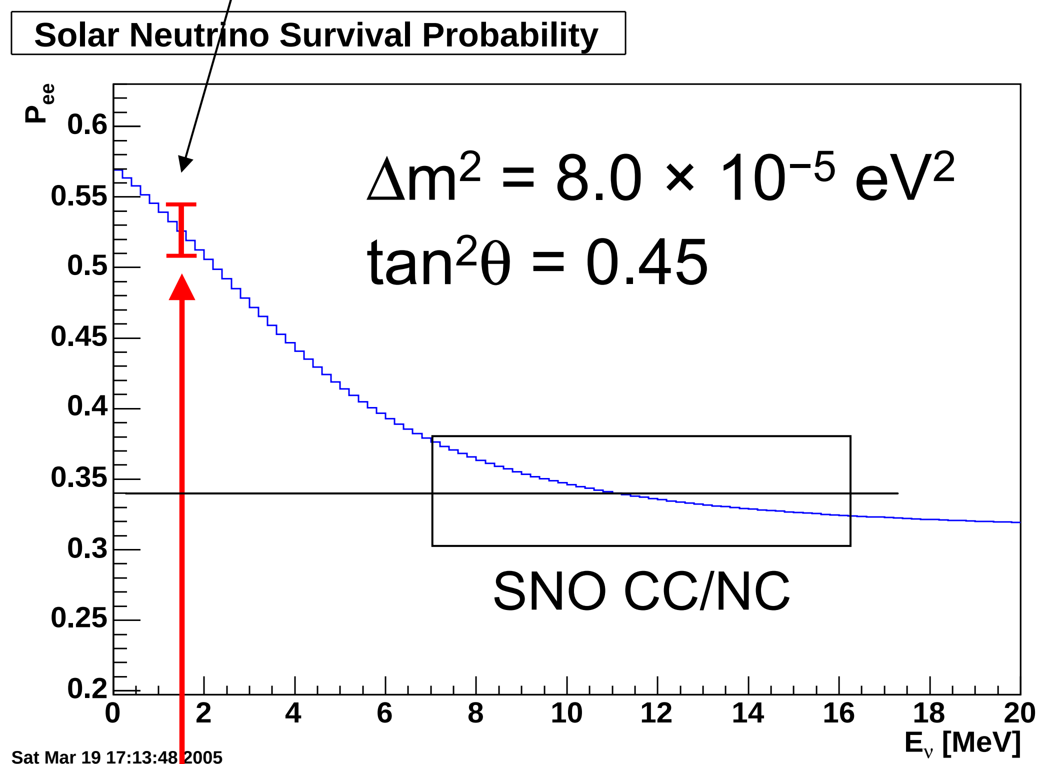
known source → precision test

improves precision on θ_{12}

sensitive to new physics:

- non-standard interactions
- solar density perturbations
- mass-varying neutrinos
- CPT violation
- large θ_{13}
- sterile neutrino admixture

stat + syst + SSM errors estimated



pep ν

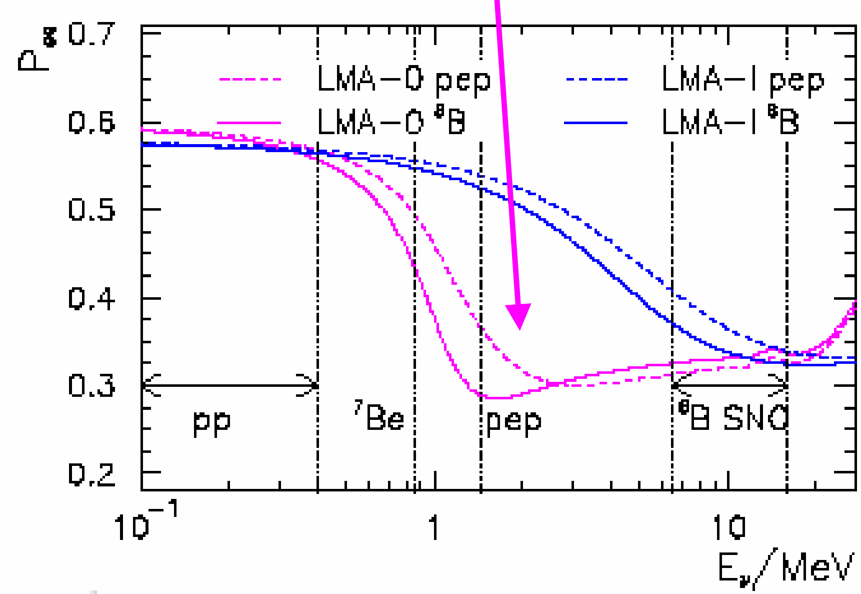
Studying the rise confirms MSW or perhaps shows us new physics

New Physics

$$L^{NSI} = -2\sqrt{2}G_F(\bar{\nu}_\alpha\gamma_\rho\nu_\beta)(\epsilon^{f\tilde{f}L}_{\alpha\beta}\bar{f}_L\gamma^\rho\tilde{f}_L + \epsilon^{f\tilde{f}R}_{\alpha\beta}\bar{f}_R\gamma^\rho\tilde{f}_R) + h.c. \quad (1)$$

NC non-standard Lagrangian

Friedland, Lunardini, Peña-Garay, hep-ph/0402266



- non-standard interactions
- MSW is linear in G_F and limits from ν-scattering experiments ∝ g^2 aren't that restrictive
- mass-varying neutrinos

~ =

$$\begin{pmatrix} -\frac{\Delta m^2}{4E}\cos 2\theta + \sqrt{2}G_F N_e & \frac{\Delta m^2}{4E}\sin 2\theta \\ \frac{\Delta m^2}{4E}\sin 2\theta & \frac{\Delta m^2}{4E}\cos 2\theta \end{pmatrix}$$

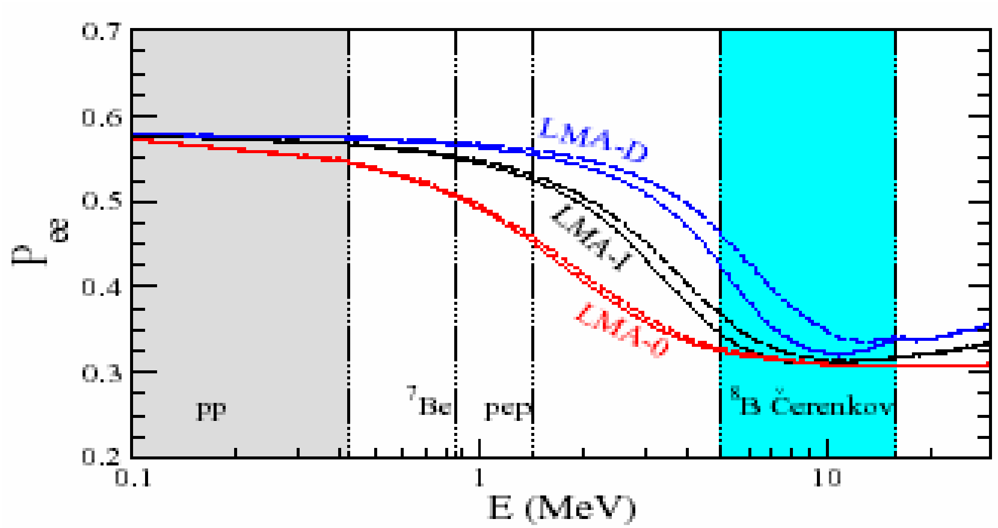
pep solar neutrinos are at
the "sweet spot" to test for new physics

New Physics

$$L^{NSI} = -2\sqrt{2}G_F(\bar{\nu}_\alpha\gamma_\rho\nu_\beta)(\epsilon^{f\tilde{f}L}_{\alpha\beta}\bar{f}_L\gamma^\rho\tilde{f}_L + \epsilon^{f\tilde{f}R}_{\alpha\beta}\bar{f}_R\gamma^\rho\tilde{f}_R) + h.c. \quad (1)$$

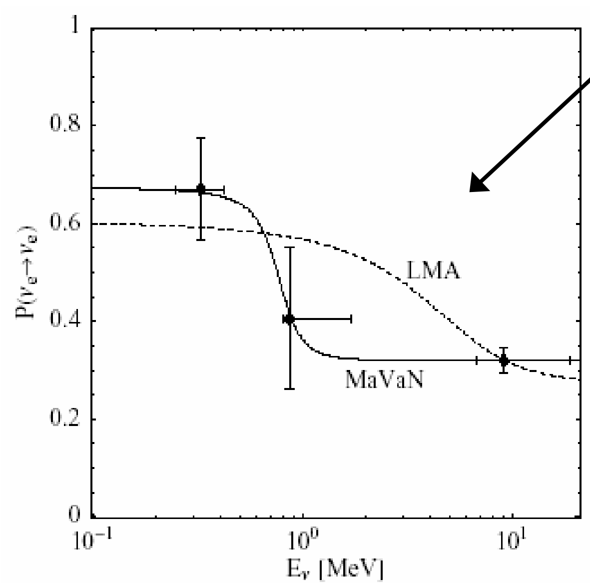
NC non-standard Lagrangian

- non-standard interactions
- MSW is linear in G_F and limits from ν-scattering experiments $\propto g^2$ aren't that restrictive
- mass-varying neutrinos



Miranda, Tórtola, Valle, hep-ph/0406280

Sterile Neutrinos:
de Holanda and Smirnov hep-ph/0307266



Barger, Huber, Marfatia, hep-ph/0502196

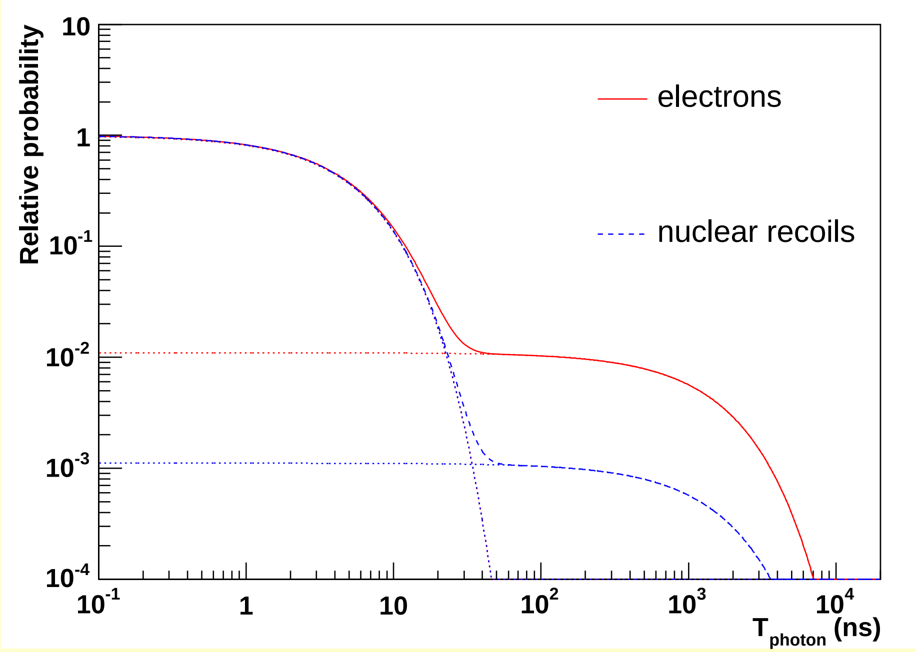
DARK MATTER

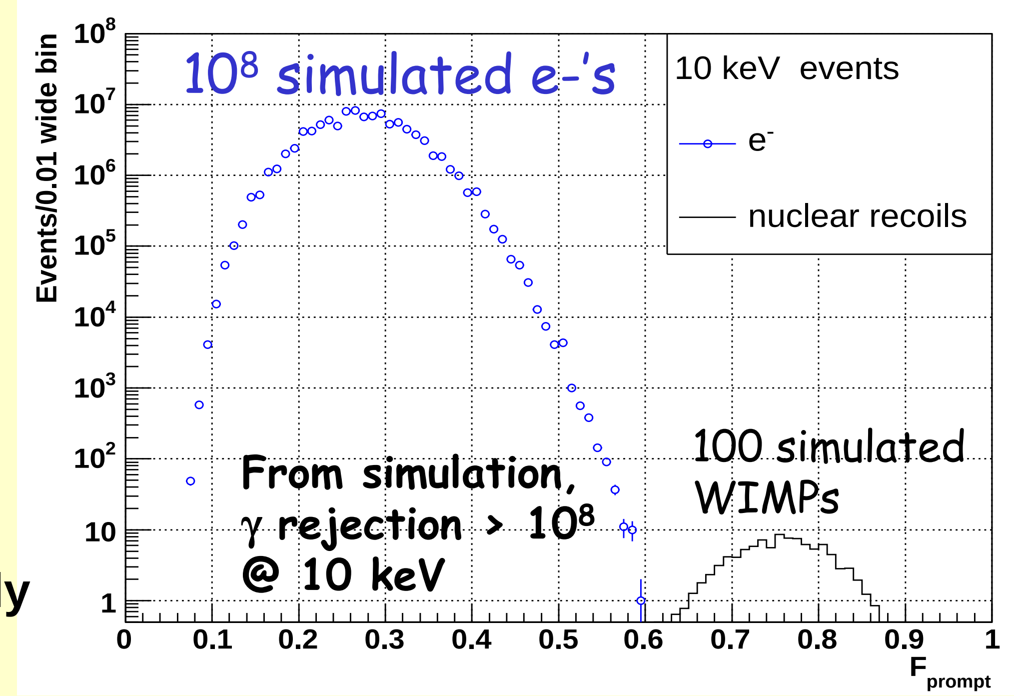
DEAP/CLEAN: 1 Tonne Fiducial Liquid Argon

- Scintillation time spectrum for Ar enables WIMP recoils to be separated from gammas from ^{39}Ar background.

- Simulation indicates that ^{39}Ar and other gamma-beta backgrounds can be discriminated from WIMPS using only scintillation light for up to 1 tonne fiducial Volume of liquid argon.

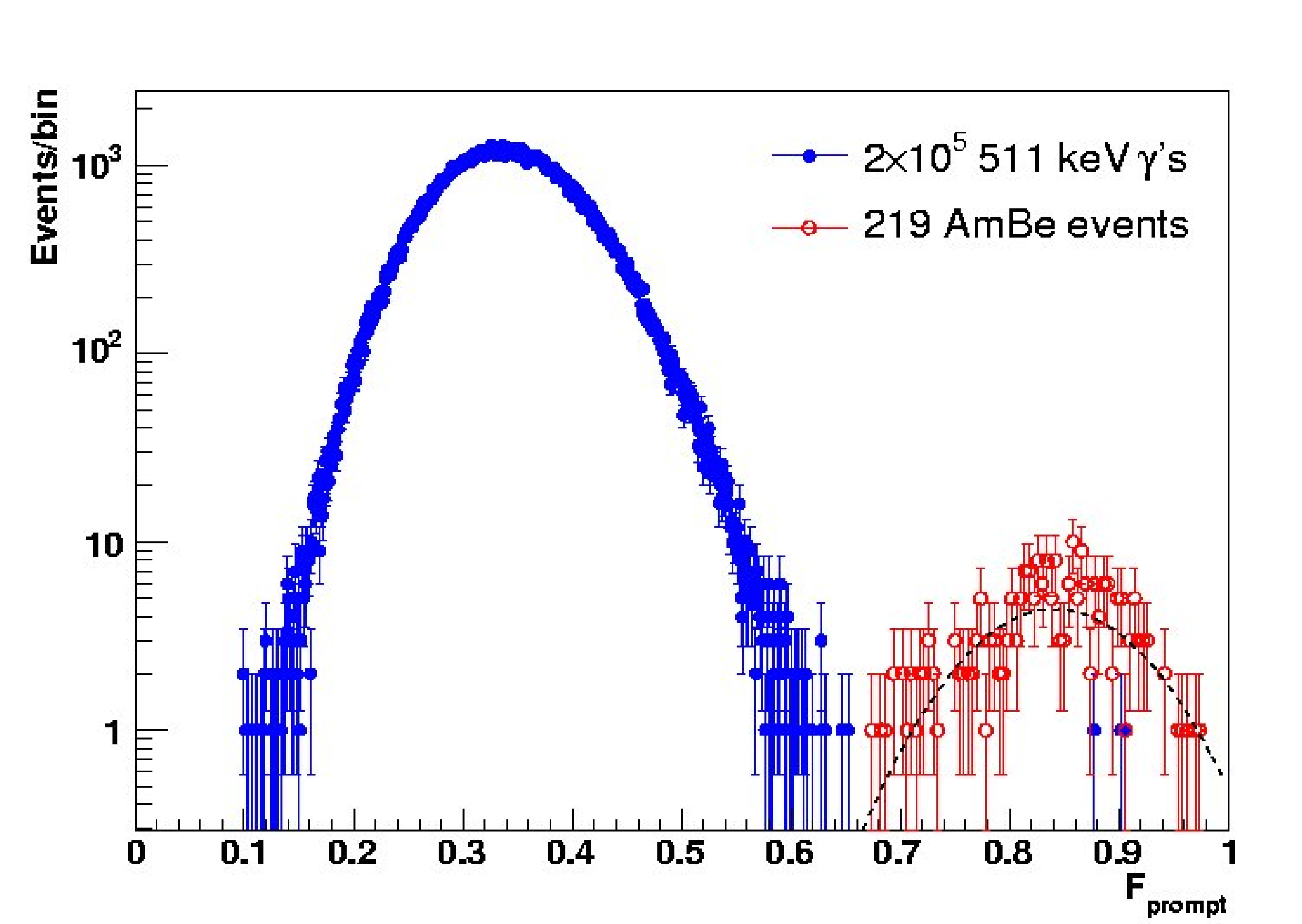
- DEAP and CLEAN collaborations have come together to build this new detector with a simple and easily scaled technology at SNOLAB.





M.G. Boulay & A. Hime, astro-ph/0411358

Discrimination in liquid argon from DEAP-0 (<1 kg)

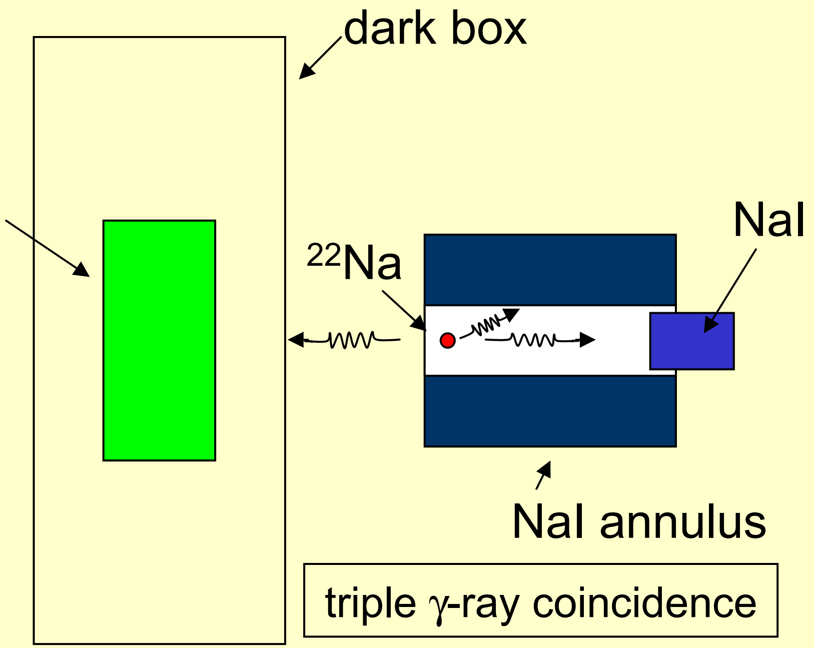


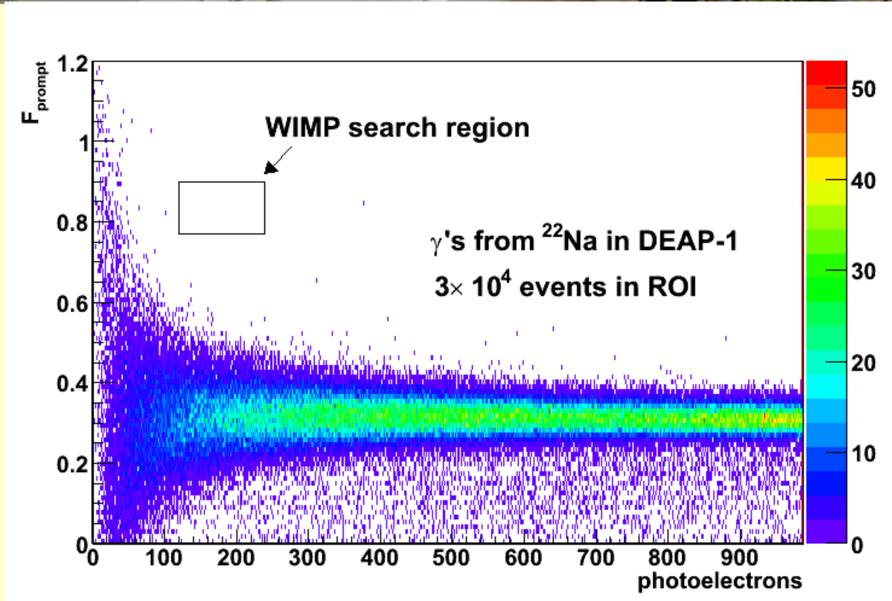
O(1in 10^5) consistent with background neutrons in surface lab.

DEAP- 1 (7 kg) Is in operation on surface. Discrimination 3 x 10^6 so far. To SNOLAB in fall 2007.

Will test Discrimination to 10^9

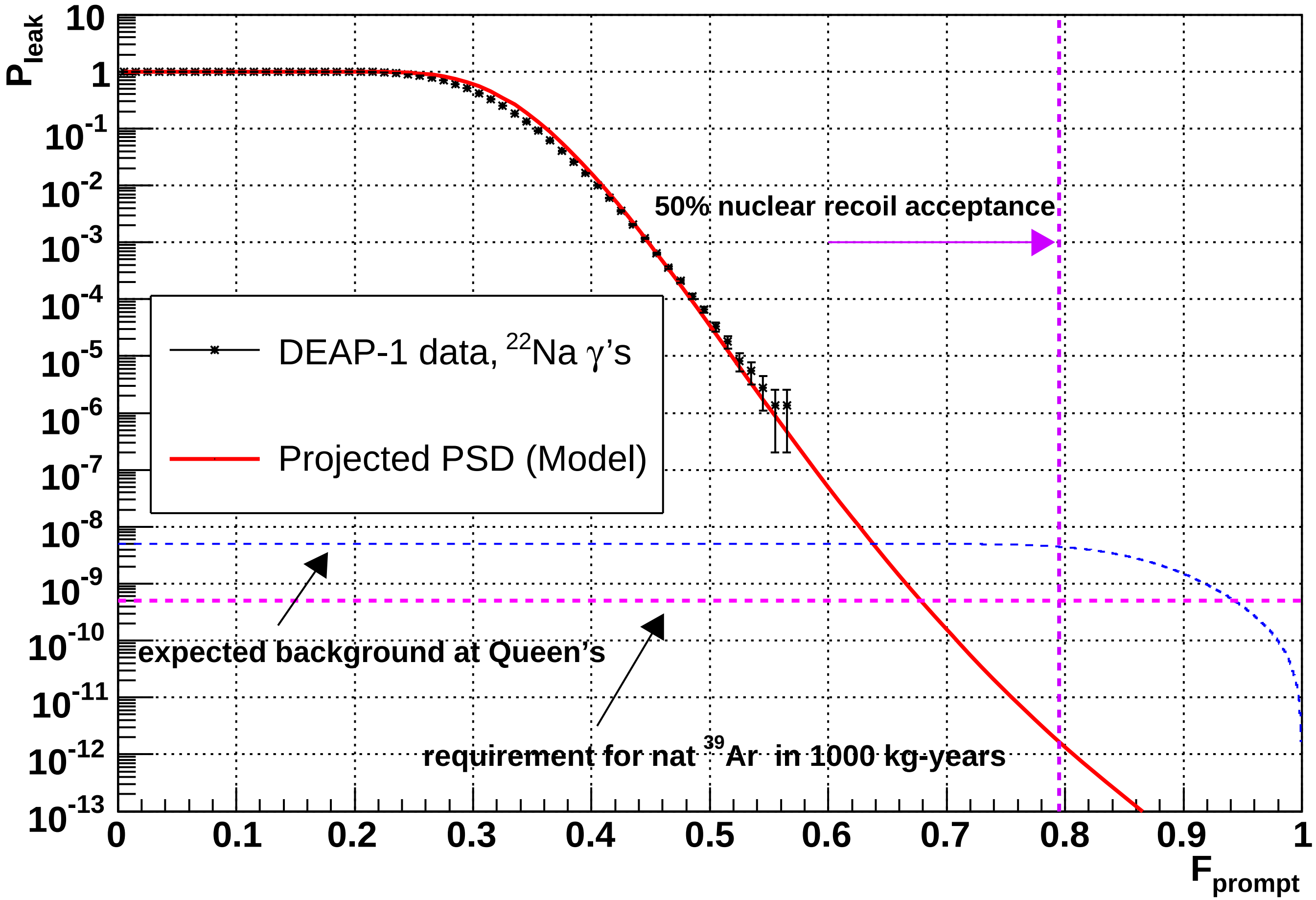
DEAP-1 pulse shape discrimination (surface runs at Queen's)





Status: running with full shielding
(8 tonnes H_2O + poly) on
surface, background < 10 mHz

DEAP-1 pulse shape statistics for 511 keV gammas (surface runs at Queen's)

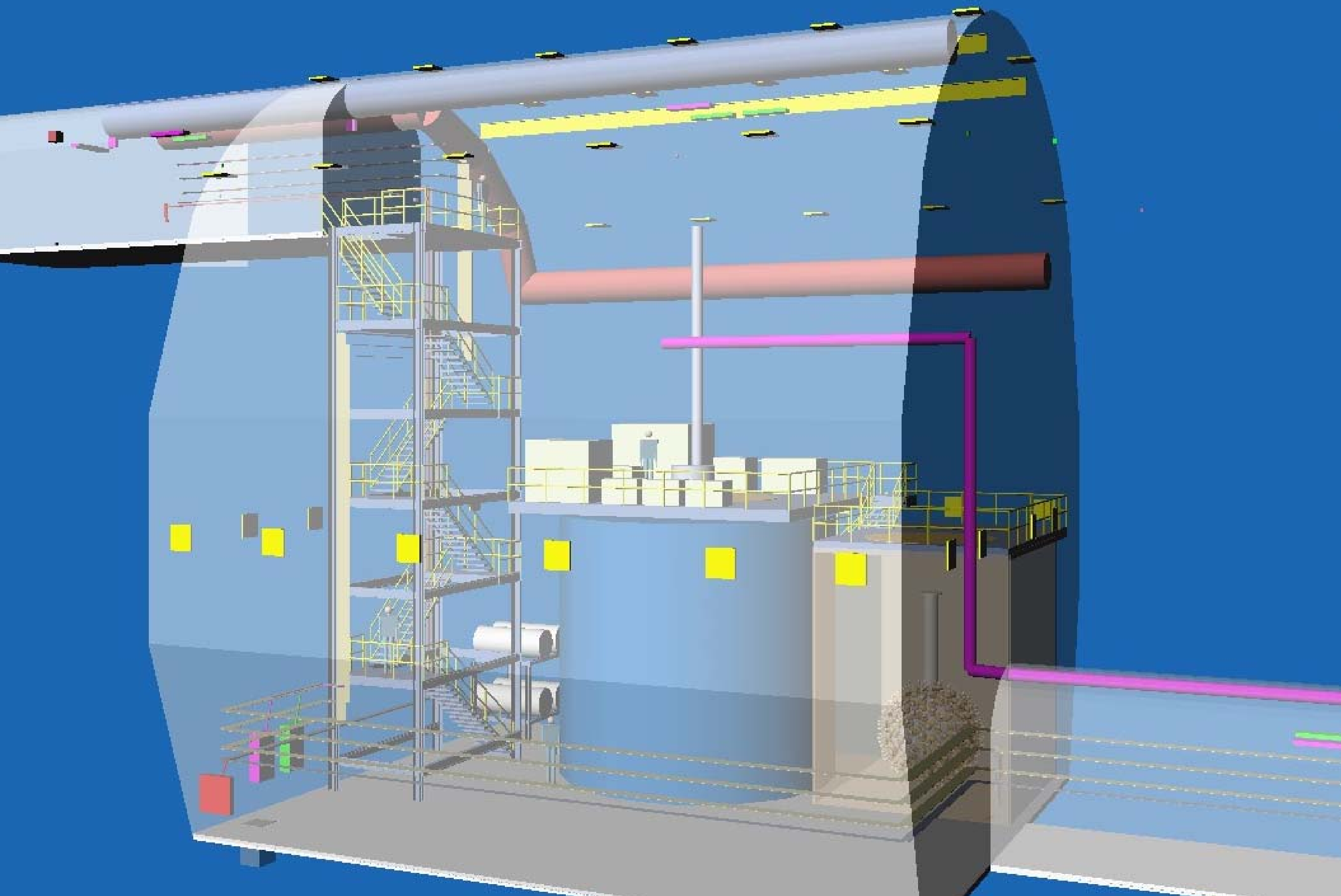


PSD agrees with statistical model over the six orders of magnitude it has currently been tested.

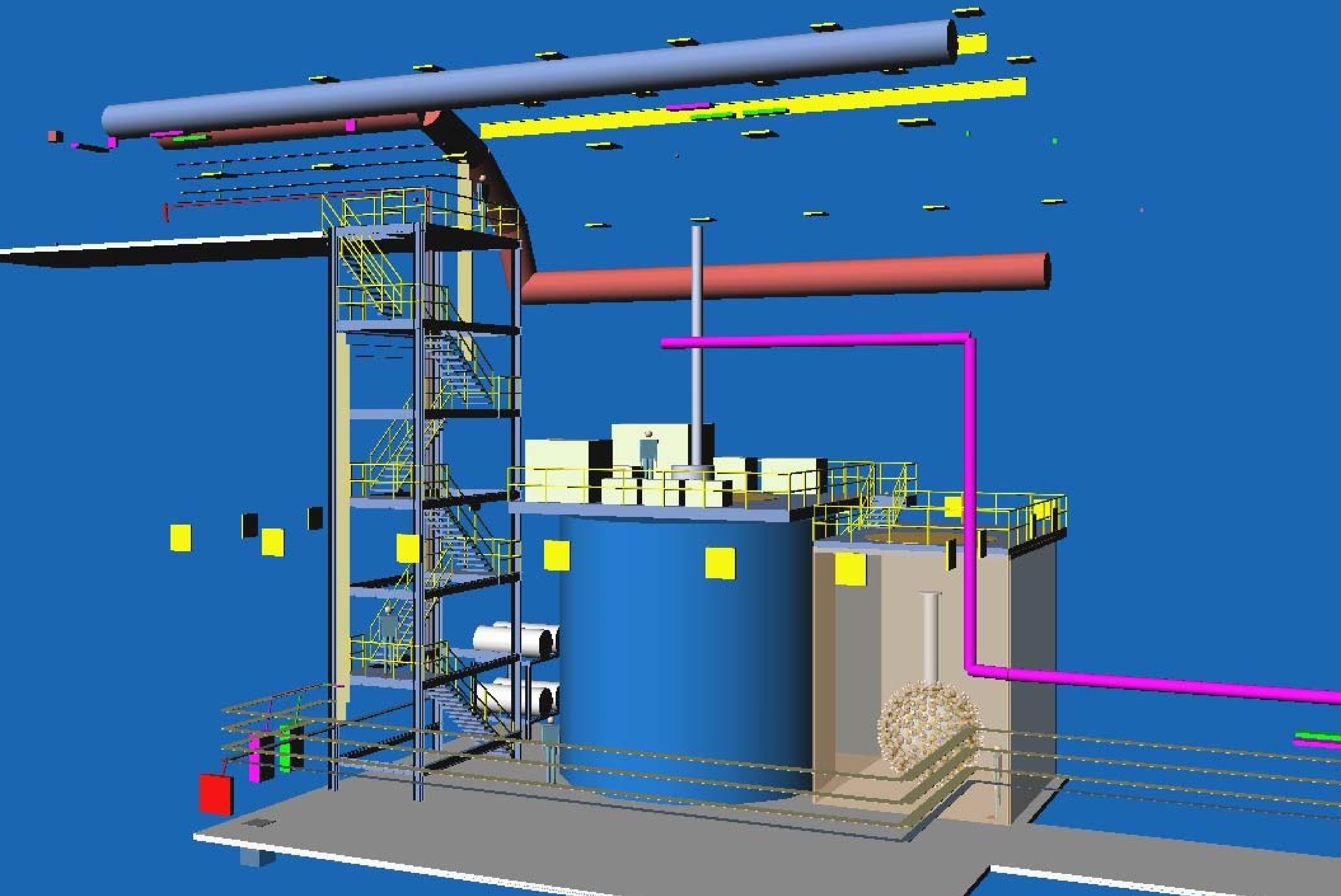
Projected to be sufficient for background reduction needed for DM search.

Will run DEAP-1 on surface until background limited (projected $<10^{-8}$ with ~15 live days of calibration data) then move to SNOLAB for further PSD studies and DM search.

DEAP/CLEAN (1 Tonne fiducial) in Cube Hall

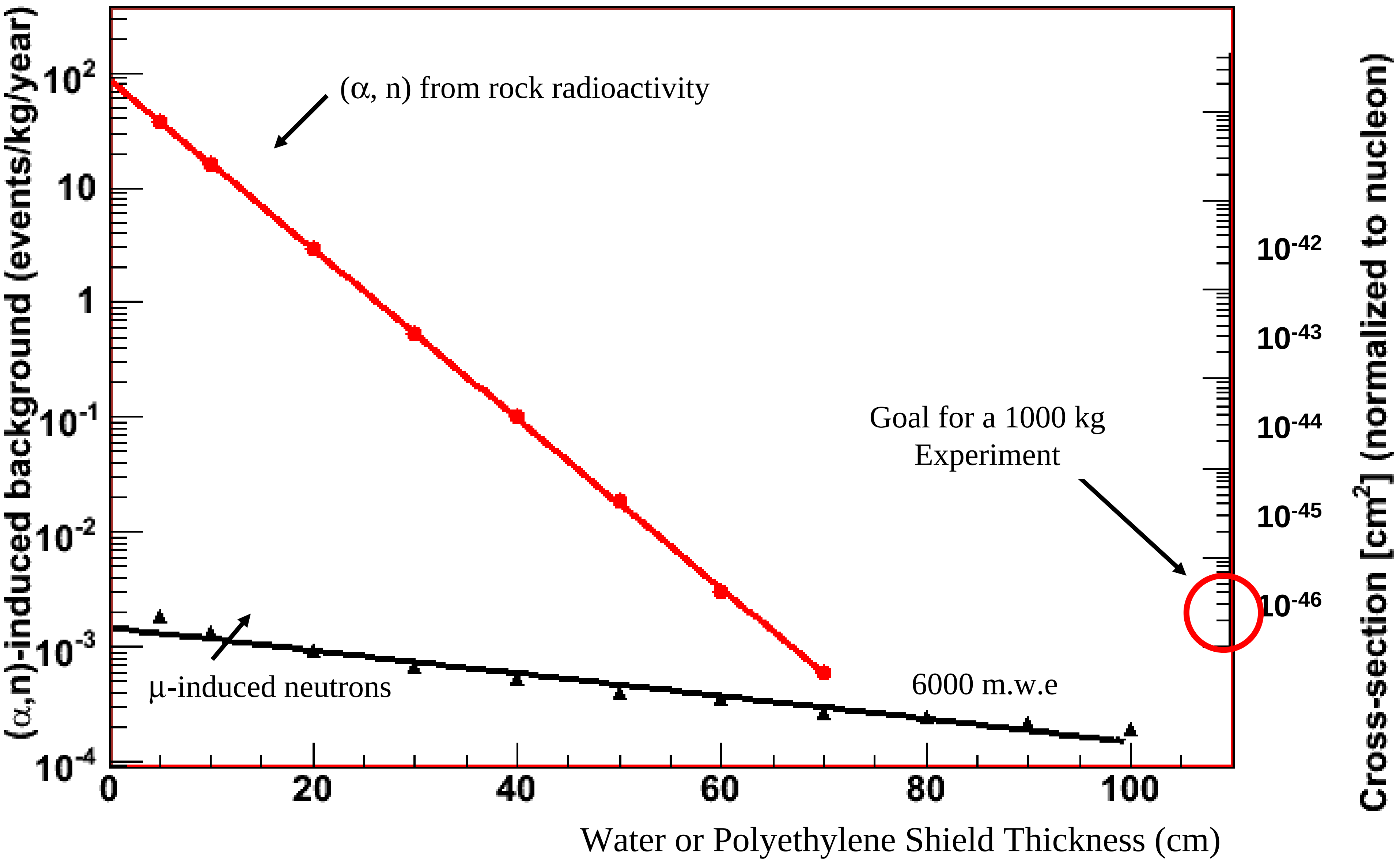


DEAP/CLEAN (1 Tonne fiducial) in Cube Hall

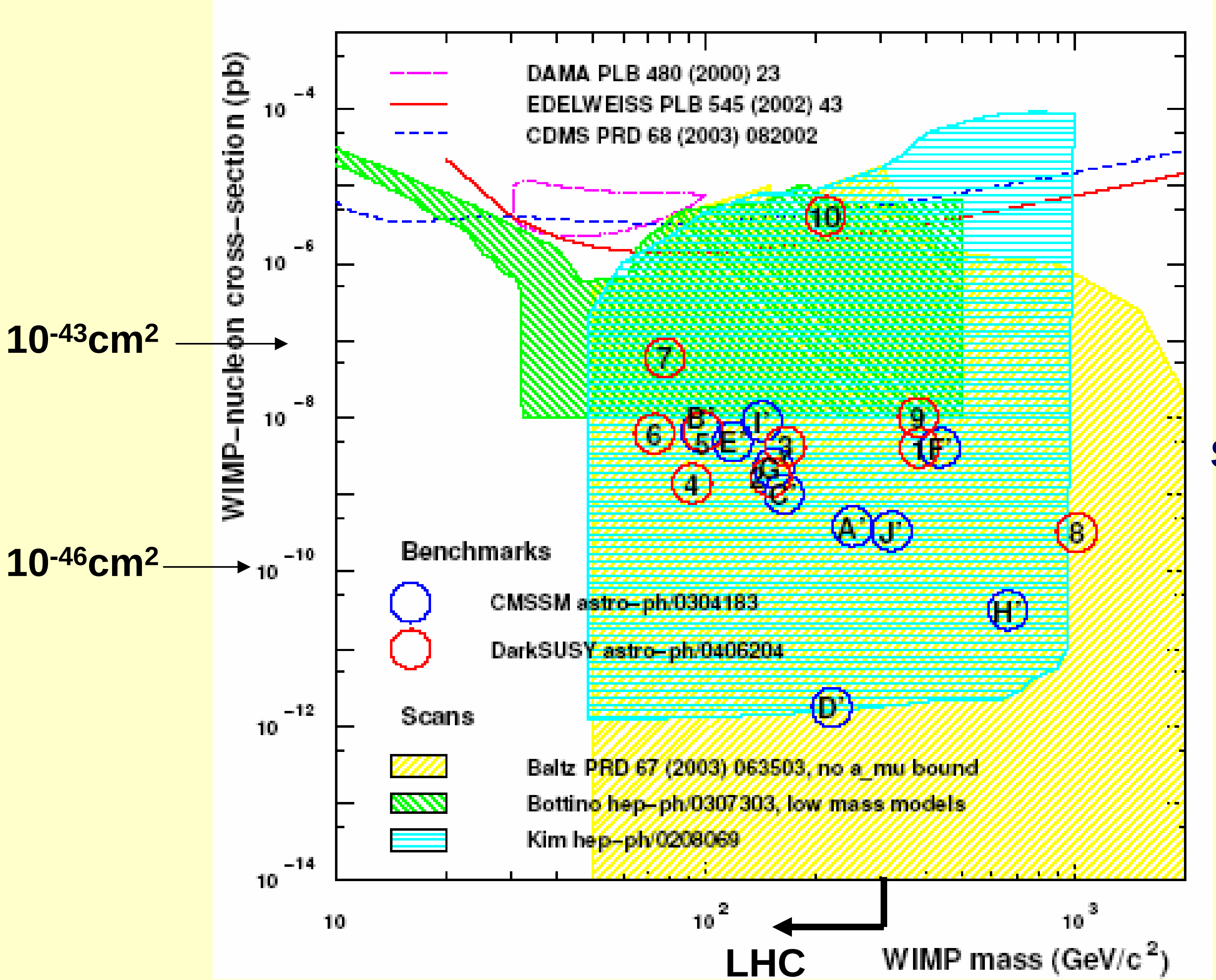


External Neutron Shielding Requirements

Mei & Hime … Following from PRD **73**, 053004 (2006)

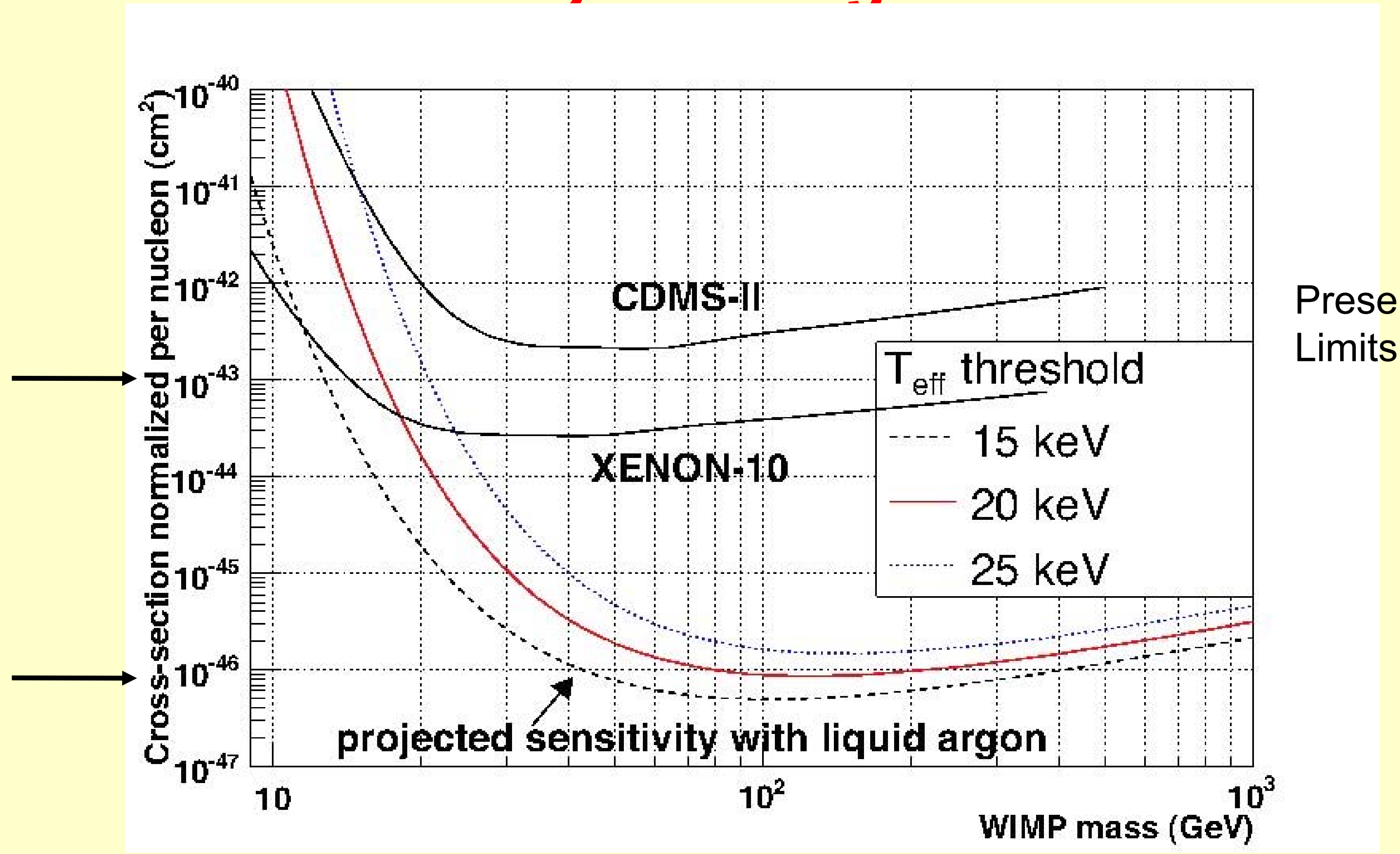


Spin Independent Interaction



Minimal Super-Symmetric Models

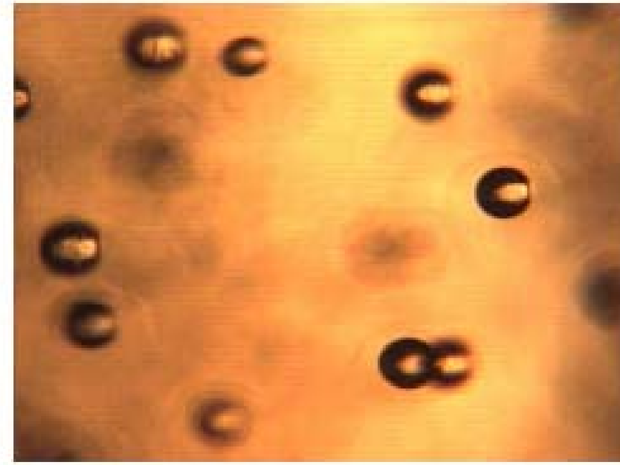
WIMP Sensitivity with argon



Present Limits

For nominal threshold of 20 keV visible energy, 1000 kg LAr for 3 years is sensitive to 10^{-46} cm^2

The Superheated Droplet Detector



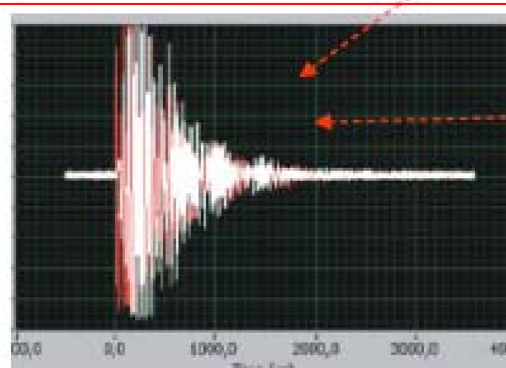
- droplets superheated at ambient T & P
- 50 to 100μm droplets of carbofluorides dispersed in polymerised gel
- active liquids:
  C_4F_{10} (T_b=-1.7 °C) , C_3F_8 (T_b=-36.7 °C)
- …used for n-dosimetry (BTI-Chalk River)
- Recoil energy threshold E_{rec} = O(keV)
- insensitive to β, γ and cosmic μ radiation

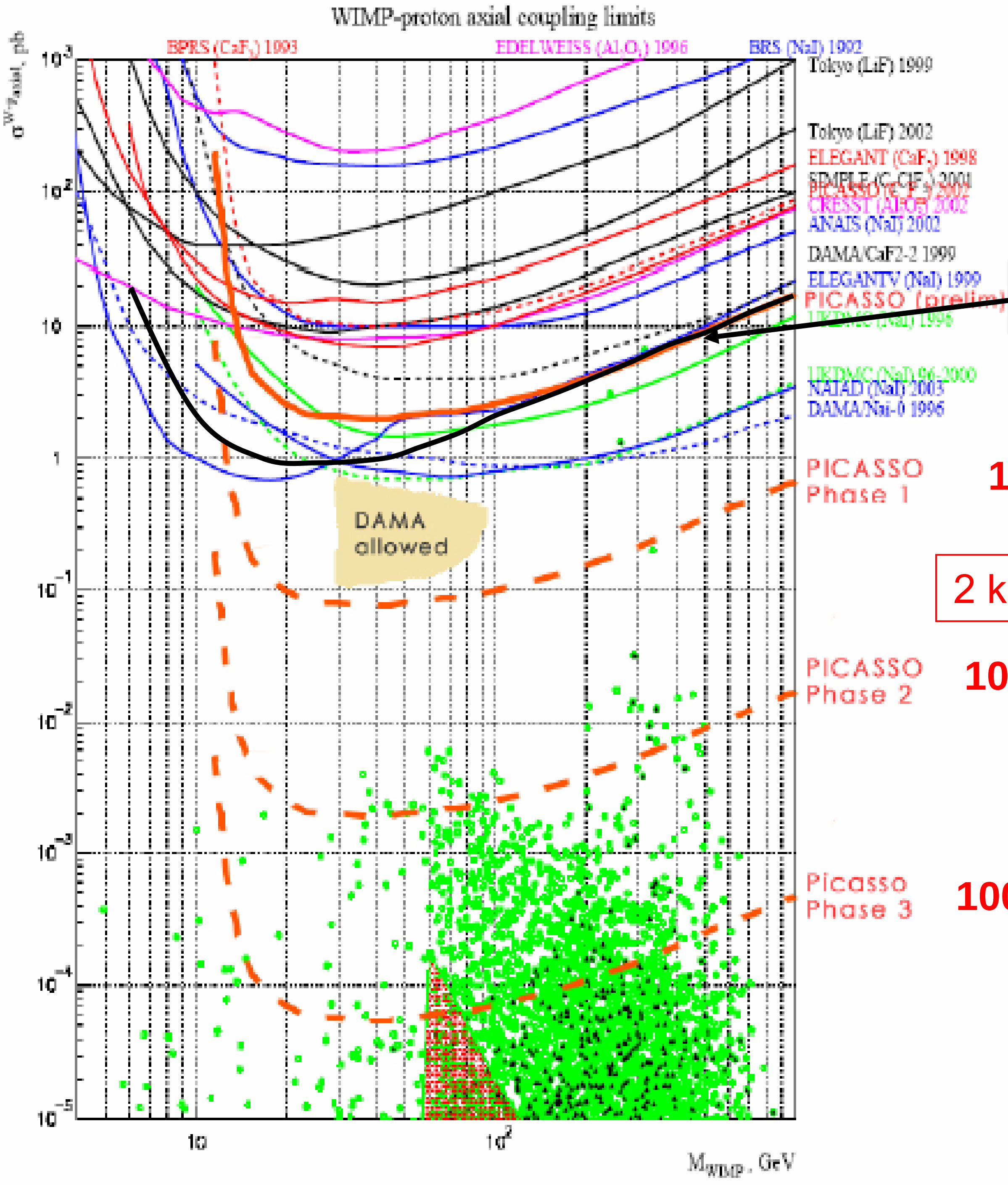
Fluorine is very sensitive for the spin-dependent interaction

Montreal, Queen's

Indiana, Pisa, BTI

Picasso





SPIN - DEPENDENT

INTERACTION

20 g: hep-ex/0502028

PICASSO

1 kg

2 kg being run in 2006-07

10 kg

100 kg

CONCLUSION

Astroparticle physics is an exciting and growing field with continuing contributions to both particle physics and astronomy.

Look for many new results in the next few years in neutrino physics, dark matter, double beta decay with the potential for fundamental discoveries.